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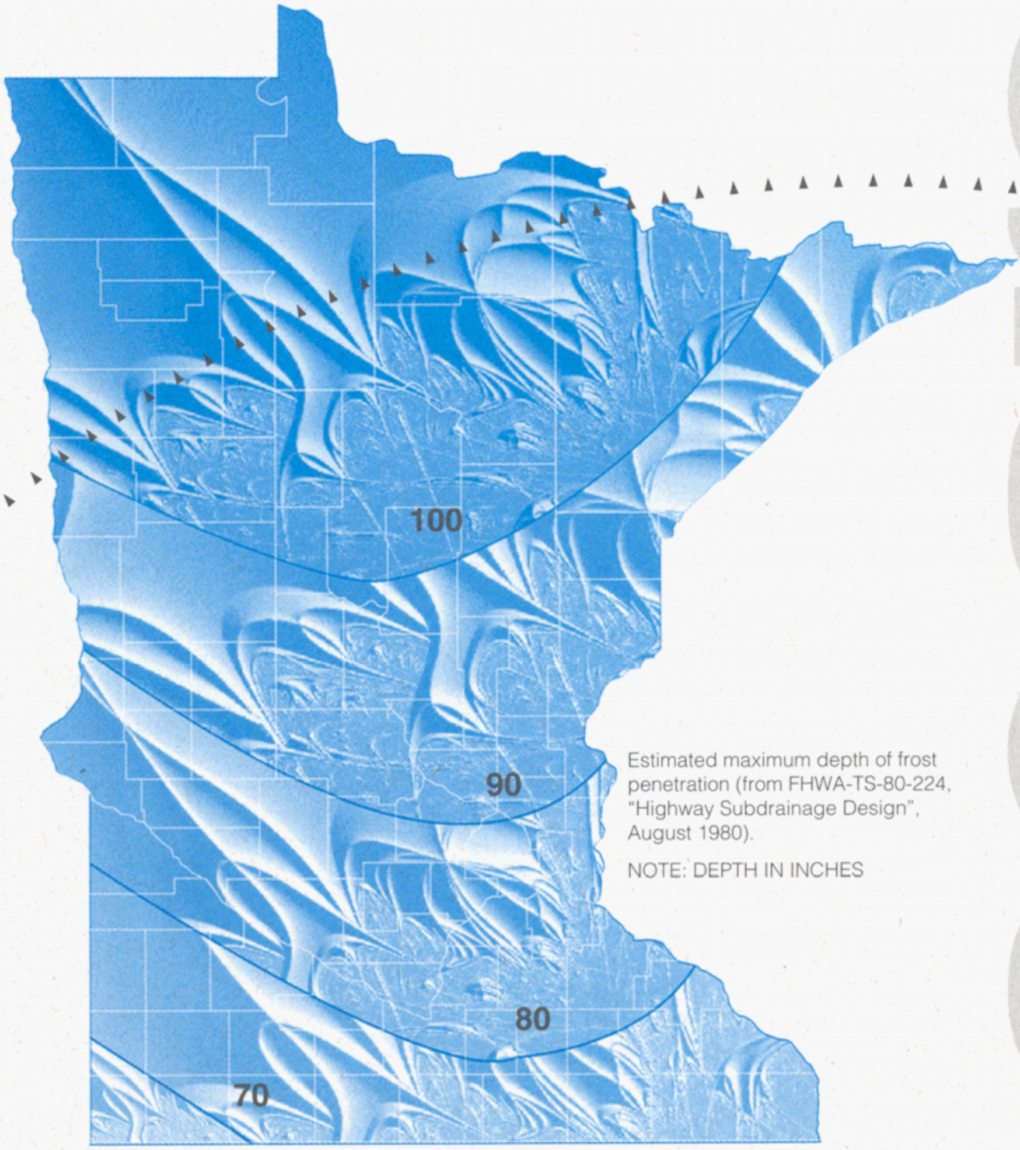

Calculated Maximum Frost Depths at Mn/ROAD

Winters 1993-94, 1994-95 and 1995-96

Local Road Research Board

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16. Abstract (Limit: 200 words)

This effort involved calculating maximum frost penetration depths for each of the 40 test cells at MnROAD, the Minnesota Department of Transportation's pavement testing facility, for the 1993-94, 1994-95, and 1995-96 winters. The report compares results with measured maximum frost penetration depths for the same three winters. Generally, calculated depths were within plus or minus 15 percent of measured depths, but differences were much greater for the four test cells underlain by the granular subgrade.

Researchers conducted sensitivity tests to determine the influence of the n-factor, soil moisture content, material density, layer thickness, thermal conductivity, mean annual soil temperature, and volumetric latent heat of fusion. Conclusions included the following:
Ñ Small variation in layer thickness will have a very minor effect on computed frost depths.
Ñ Reasonable variations in moisture content and density of the various base course, subbase course, and subgrade layers will have a minor effect on calculated frost penetration depths.
Ñ Large n-factors caused deeper calculated frost penetration depths, and the use of n-factors of .90 and .95, respectively, for flexible and rigid pavements provided the most reasonable estimates of frost depths.
Ñ Increasing the thermal conductivity of the materials by 25 percent resulted in closer calculated agreement with measured frost depths.
Ñ Using a mean annual soil temperature of 9.4√ C rather than 11.1√ C resulted in better agreement between calculated and measured data.

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CALCULATING MAXIMUM FROST DEPTHS IN MN/ROAD TEST CELLS

Winter 1993–94, 1994–95 and 1995–96

Final Report

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When these data were used in the Modified Berggren Equation to calculate frost depths, the calculated depths were generally within ±18.9% of the measured depths. When the test cells containing only the fine-grained subgrade were considered, the majority of the calculated depths were within ±13.3% of the measured depths.

Results from this effort indicated that two studies should be initiated at Mn/ROAD to explain, at least in part, the differences between the calculated and measured maximum seasonal frost penetration depths;

- Evaluate changes in subsurface moisture contents, especially in the freezing zone beneath each test cell, during the three years.
- Install instruments to measure pavement surface temperatures, in at least some of the test cells.

EXECUTIVE SUMMARY

The Modified Berggren Equation, MBE, has been used to compute maximum seasonal frost depths beneath roadway and airport pavements for nearly 40 years. The specific objective of this effort was to use the MBE to compute maximum seasonal frost penetration depths for each of the 40 Mn/ROAD test cells for the 1993–94, 1994–95 and 1995–96 winters. Mn/ROAD researchers measured frost depths at each of the 40 test cells several times each winter using electrical resistivity gauges. Measured maximum frost depths for each winter for nearly all test cells were compared to depths calculated from the MBE. Reasons for differences between the measured and calculated maximum frost penetration depths are discussed and conclusions and recommendations for future work are presented.

For the 1993-94 winter, measured frost depths were available for 29 of the test cells and calculations were made for all 40 test cells. In all test cells except those with the granular subgrade, calculated frost depths were within ±20% of the measured depths and most were within ±10%. In most cells, the calculated values were less than the measured depths. The freezing season extended from November 5, 1993, to March 12, 1994, and the air freezing index was 1143 °C-days (2057 °F-days).

For the 1994–95 winter, measured frost depths were available for 30 of the test cells. Again calculations were made for all 40 cells. The vast majority of the calculated frost depths were greater than the measured depths; only two of the measured depths were less than the computed values. Nineteen of the calculated values were within ±20% of the measured depths and the rest exhibited greater differences. The freezing season ran from November 21, 1994, through March 10, 1995, with an air freezing index of 895 °C-days (1611 °F-days).

For the 1995–96 winter, measured frost depths were again available for 30 of the test cells. Computations were made for all 40 cells. In 26 of the cells, calculated frost depths were within ±20% of the measured depths, and in 21 of the cells the calculated and measured values were within ±10%. The freezing season for this year extended from November 2, 1995, through April 8, 1996. It was the coldest of the three winters, having an air freezing index of 1344 °C-days (2419 °F-days).

For all three winters, calculated frost penetration depths were much greater than the measured depths for the four test cells containing the granular subgrade. The author suspects that the measured depths are in error for these test cells and recommends that Mn/ROAD researchers reexamine the measured data from these test cells.

Sensitivity tests were conducted on the properties of the pavement materials, moisture content, density and layer thickness, as well as the mean annual soil temperature, n-factor, thermal conductivity and latent heat of fusion of the subgrade soil. Conclusions developed from the sensitivity studies included:

- Small variations in layer thickness will have a very minor effect on computed frost depths and can reasonably be neglected.
- Reasonable variations in moisture content and density of the various base course, subbase course and subgrade layers will have a minor effect, usually less than 10%, on calculated frost penetration depths.
- Larger n-factors caused deeper calculated frost penetration depths, and the use of n-factors of 0.90 and 0.95, respectively, for flexible and rigid pavements provided the most reasonable estimates of frost depth.
- Increasing the thermal conductivity of the materials by 25% resulted in closer calculated agreement with measured frost depths.
- Using a mean annual soil temperature of 9.4°C (49.0 °F) rather than 11.1 °C (51.9 °F) resulted in better agreement between calculated and measured data.

Figure

TABLES

Table

Calculating Maximum Frost Depths in Mn/ROAD Test Cells
Winter 1993–94, 1994–95 and 1995–96

RICHARD L. BERG

INTRODUCTION

Since Mn/ROAD is in an area where the pavement, base, subbase and subgrade materials freeze and thaw one or more times during the year, the pavement system must be designed to withstand freeze–thaw effects. This report presents a procedure for calculating the maximum frost penetration depth beneath each test cell during winter.

The specific objective of this study was to compute frost depths beneath each of the 40 Mn/ROAD test cells for the winters of 1993–94, 1994–95 and 1995–96.

Computed depths are compared with measurements in most of the cells for each of the winters, and reasons for differences between the calculated and measured values are discussed. Conclusions and recommendations for additional studies are presented.

MODIFIED BERGGREN EQUATION

Background and Theory

The Modified Berggren Equation (MBE) was developed by Aldrich and Paynter (1953) for the U. S. Army Corps of Engineers. It is a relatively simple procedure based on Stefan's method for estimating the thickness of ice on large bodies of water. The general form of the equation for a homogeneous material is:

$$x = \lambda\sqrt{(48knF)/L} \tag{1}$$

where x = maximum frost depth (ft)

k = thermal conductivity (Btu/ft hr °F)

n = n-factor to convert an air freezing index to a surface freezing index, dimensionless

F = air freezing index (°F-days)

L = volumetric latent heat of fusion (Btu/ft^3)

λ = a dimensionless factor to account for the effects of the initial temperature conditions not being isothermal at 32°F. It is influenced by the thermal properties of the soil as well as the mean annual temperature (MAT), the freezing index, and the length of the freezing season. Its value is always less than 1.0 for freezing conditions. More information about this coefficient is available in Aldrich and Paynter (1953).

Because the MBE was developed in the U.S. in the early 1950s, the English system of units was used. These units were therefore used in making calculations in this report.

Pavements are layered systems, so the MBE was rearranged to consider the effects of layering. Aitken and Berg (1968) wrote the first computer program to solve the layered form of the MBE; it has been revised by others at the U.S. Army Cold Regions Research and Engineering Laboratory to run on a personal computer. A version of the program prepared in about 1988 was used in this study. The MBE for a pavement layer is:

$$nF_\ell = \frac{t^2 L_\ell}{48 k_\ell \lambda_\ell^2} \tag{2}$$

where t is the thickness of a particular layer (ft) and the remainder of the parameters are as defined above, but for the specific layer, ℓ, under consideration.

When this form of the equation is used, the index required to freeze each layer is computed, and when the total for a sequence of layers equals the surface freezing index, a solution is obtained. The thickness of the last layer is determined by trial and error. Generally for this Mn/ROAD study, frost penetrated into the subgrade, which was usually the third or fourth layer in the pavement system.

Freezing index

As indicated in equation 1, the maximum frost penetration depth is directly proportional to the square root of the freezing index. Therefore, a greater freezing index will result in greater frost penetration.

The freezing index is determined by algebraically summing the daily degree days for a period which includes the "freezing season." For example, in Minnesota one could use the period from October 1 of one year to May 1 of the following year. The degree days (DD) for each day are computed from the difference between the average daily temperature, ADT, and the freezing point of bulk water, T_f. In equation form:

$$DD = ADT - T_f \qquad (3)$$

where DD = degree days for a specific day and the other terms were defined above.

Equation 3 is valid in either the English or the International System of units. Table 1 illustrates the procedure for a hypothetical 10-day period.

Table 1. Computation of degree days and cumulative degree days.

Date	*ADT* (°F)	T_f (°F)	*DD* (°F)	*Cum DD* (°F)
October 1	39.0	32.0	+7	+7
October 2	33.5	32.0	+1.5	+8.5
October 3	31.0	32.0	−1.0	+7.5
October 4	27.5	32.0	−4.5	+3.0
October 5	24.5	32.0	−7.5	−4.5
October 6	29.0	32.0	−3.0	−7.0
October 7	31.5	32.0	−0.5	−7.5
October 8	37.5	32.0	+5.5	−2.0
October 9	30.5	32.0	−1.5	−3.5
October 10	36.0	32.0	+4.0	+0.5

1°F = 0.56°C for Cum DD.
1°F = $^5/_9$(F−32)°C for temperatures.

If the process in Table 1 were continued until May 1 of the following year, and the cumulative degree days versus time plotted, a graph similar to Figure 1 would be produced. Figure 1 contains data for the 1983–84 winter at Buffalo, Minnesota, which is the weather station nearest to Mn/ROAD with long-term (>30 years) records. Buffalo is about 8 miles southeast of the Mn/ROAD test site. The data in Figure 1 start on October 1, 1983, and end on May 1, 1984. The difference between the highest point (358.5°C-days or 645.3°F-days on day 51, November 21,1983) and the lowest point (−821.0 °C-days or −1477.8°F-days on day 171, March 21, 1984) is the freezing index: 1179.5°C-days or 2123.1°F-days. The number of days between the highest and lowest points on the cumulative degree day curve is the length of the freezing season: 120 days for this winter.

Several observations can be made from the cumulative degree day curve for a particular year. For example, several inflection points occur between days 50 and 170. The more steeply the curve dips downward the more rapidly degree days are accu-

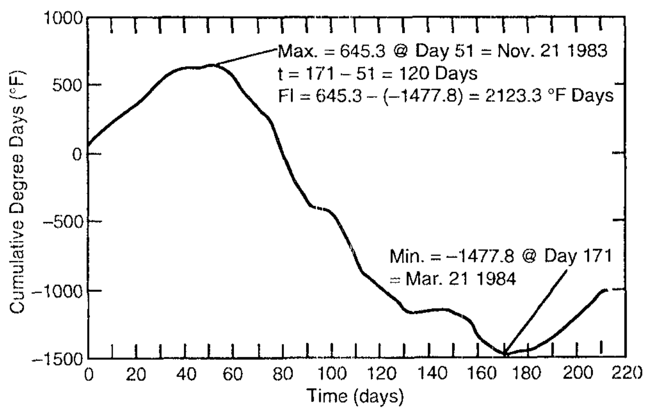

Figure 1. Cumulative degree days at Buffalo, Minnesota, during the1983–84 winter.

Table 2. Freezing index values for Mn/ROAD. Data obtained from Mn/ROAD and other nearby locations.

Winter	*Begin freezing*	*End freezing*	*Season length (days)*	*Freezing index (°C-days)*	*Freezing index (°F-days)*
1991-92	29 Oct 91	2 Mar 92	125	767	1381
1992-93	3 Nov 92	23 Mar 93	140	1078	1940
1993-94	5 Nov 93	12 Mar 94	127	1143	2057
1994-95	21 Nov 94	10 Mar 95	109	895	1611
1995-96	2 Nov 95	8 Apr 96	158	1344	2419
Average			132	1045	1882
30-yr norm	11 Nov	20 Mar	125	944	1699

Note: Data provided by Craig Schrader, MN/DOT, on 22 October 1996.

mulating, i. e. the days are colder. When the curve moves upward, as it does between days 94 and 97 and days 132 and 146, thawing periods have occurred.

Craig Schrader, MN/DOT, provided freezing index values for each of the three winters used in this study (1993–94, 1994–95 and 1995–96), as well as for the 1991–92 and 1992–93 winters, and the 30-year average freezing index for Buffalo, Minnesota (Table 2).

Bigl and Berg (1996) estimated pavement performance for a 21-year period at Mn/ROAD using data from Buffalo, Minnesota. The largest freezing index for the period was 1477 °C-days (2658 °F-days) during the 1978–79 winter, and the smallest was 467 °C-days (841 °F-days) during the 1986–87 winter. The average of the two coldest winters in the period was 1404 °C-days (2526 °F-days). The Corps of Engineers would generally use this value as the design freezing index (DFI) for a site.

The data in Table 2 indicate that the 94–95 winter was about 5% lower than the average, or mean, freezing index (MFI) in the area, and that the 95–96 winter was about 4% lower than the DFI. Thus by including these two winters in the calculations, estimates of frost penetration for about an "average" winter and for a very cold winter will be obtained.

The discussion above has concerned air temperatures and freezing indexes computed from them. To determine frost depths beneath pavements using the Modified Berggren Equation, one must know the freezing index at the pavement surface. Since these values are seldom measured (at Mn/ROAD this is the case), estimates are made based on the air freezing index values. The surface freezing index is generally obtained by multiplying the air freezing index by an n-factor. N-factors for freezing conditions are less than 1.0 because the pavement surface absorbs radiant energy from the sun and heat is added to the pavement surface by conduction of heat from below the pavement. N-factors less than 1.0 indicate that the pavement surface temperature is greater than the air temperature. Lunardini (1981) summarizes n-factors for a variety of surfaces and locations. N-factors for asphalt pavements range from 0.25 to 0.96 and for PCC pavements from 0.12 to 0.87. The larger n-factors were generally measured at higher latitudes where the daily quantities of solar radiation are smaller in the winter. Kersten (1959) reviewed n-factor data from Minnesota and indicated that values ranged from 0.74 to 0.80.

For this contract, I conducted a small sensitivity study. I allowed n-factors to vary from 0.7 to 0.9 on AC pavements and from 0.75 to 0.95 on PCC pavements. Details of this sensitivity study are presented later (*Sensitivity Studies*, p. 9).

Mean annual temperature

The mean annual temperature (MAT) impacts on the value of λ in Equations 1 and 2. Generally, a higher average annual temperature will result in a lower value of λ. The primary reason for this is that the entire soil mass is assumed to be at the MAT just prior to the onset of freezing conditions. A warmer soil mass results in less frost penetra-

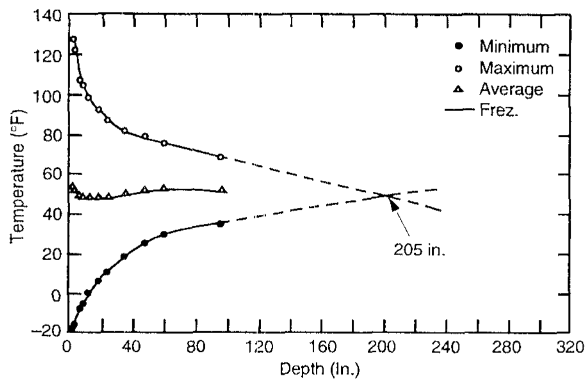

Figure 2. Maximum, minimum and average subsurface pavement temperatures in Test Cell 29 during 1996.

tion because low surface temperatures must cool the soil mass to freezing prior to the onset of frost penetration.

Since frost is penetrating into the material beneath the pavement, the mean annual soil temperature must be used rather than the mean annual air temperature. Soil and pavement surface temperatures are usually greater than air temperatures, mainly due to the absorption of solar radiation at the pavement surface. The resulting mean annual soil temperature is also greater than the mean annual air temperature. Experience has shown the difference to be 1.7°C to 5.6°C (3°F to 10°F). A reasonable average temperature difference is about 3.3°C (6°F).

Craig Schrader, MN/DOT, provided maximum, minimum and average subsurface temperatures beneath Cell 29 in 1996. Figure 2 was prepared using those data. Temperatures were extrapolated to and slightly beyond the depth where the average temperature amplitude is 0. This is the depth at which the average annual soil temperature is normally determined. At Cell 29, the depth of 0 temperature amplitude was about 5.2 m (17 ft) and the temperature at that depth was 9.4°C (49°F). The average of all of the measured values, to a depth of about 2.4 m (8 ft), was 11.1°C (51.9°F). A small sensitivity study was conducted to examine the effect of MAT on calculated frost depths at Mn/ROAD. More details on the study are in the *Sensitivity Studies* section of this report.

Thermal properties

Thermal properties of the pavement layers influence the rate of frost penetration and the total depth of frost penetration. The properties which are considered in the Modified Berggren Equation are:

Volumetric latent heat of fusion (L)
Volumetric heat capacity (C)
Thermal conductivity (k)

All three properties are influenced by the density and moisture content of the materials and to a lesser extent by the mineralogy of the soil components. The two most important properties are L and k. Examining their effect on the frost depth in Equation 1, one notes that an increase in k will increase the frost depth, whereas an increase in L will decrease the frost depth. Both properties tend to increase with increasing moisture content; therefore, it is difficult to state that an increase in moisture content will increase or decrease the maximum frost depth. Generally, however, frost will penetrate more deeply into lower moisture content materials than into higher moisture content ones. Sensitivity tests were conducted on the effects of changes in density, moisture content and thermal conductivity. The results of all three sensitivity studies are discussed in the *Sensitivity Studies* section.

The thermal conductivity was computed using the equations developed by Kersten (1949). In Kersten's equations, thermal conductivity values are dependent on the soil type (granular or fine-grained), density, moisture content and the state of the soil moisture (frozen or thawed). Values for L and C are determined from the following equations:

$$L = 144\,\gamma_d\, w/100 \qquad (4)$$

$$C = \gamma_d\,(c_s + 0.75w/100) \qquad (5)$$

where γ_d = dry density of the material (lb/ft^3)
w = moisture content (% by dry weight)
c_s = specific heat capacity of mineral solids; a value of 0.17 is used in the Modified Berggren Equation computer program.

Pavement layers

Material types and classifications, layer thicknesses, layer moisture contents, and layer densities are necessary to solve the Modified Berggren Equation. This information was provided by MN/DOT. More detailed information on the pavement layers is presented in the *Material and Layer Properties* section.

MEASURED FROST DEPTHS

Craig Schrader, Mn/ROAD, provided measured frost penetration depths for most of the test cells for each of the three winter seasons for which frost depths were calculated. The frost depths were obtained from electrical resistivity gauge data in each of the test cells. Atkins (1979) described the theory and fabrication details for this type of sensor.* The electrical resistivity gauges at Mn/ROAD are about 2.1 m (7 ft) long, and the top of each gauge is 300 mm (12 in.) below the pavement surface. Sensor wires were placed at 50-mm (2-in.) intervals along a plastic rod.

Figure 3 illustrates frost depths determined from the electrical resistivity gauge observations. The data are reasonably consistent with the freezing index data in Table 2. The 94–95 winter was the warmest, and the maximum frost depths are less in that year than in either the 93–94 or 95–96 winters. However, frost depths for the 95–96 winter are generally slightly less than those for the 93–94 winter, although the freezing index for the 95–96 winter was about 15% greater than that for the 93–94 winter. The reasons for this difference are not apparent from the data used in this study, but it could have been caused by changes in subsurface moisture conditions, changes in surface conditions, or characteristics of the two winters. None of these possibilities were studied in this investigation.

Electrical resistivity gauges indicate a frozen situation when a substantial portion of the pore water in a soil has frozen. A frozen condition causes the electrical resistivity value to increase. Figure 4 illustrates data from Cell 14, a "full depth" asphalt section, on January 25, 1995. Outputs from several of the uppermost sensors have significantly increased in value, indicating that the subgrade is frozen to a depth of about 710 mm (28 in.), a partially frozen zone reaches from 710 mm to about 860 mm (34 in.), and the remainder is unfrozen. This information infers that the temperature of the frozen material identified by electrical resistivity gauge measurements is less than the freezing point of bulk water. One reason for this may be that all of the water in the subgrade soils

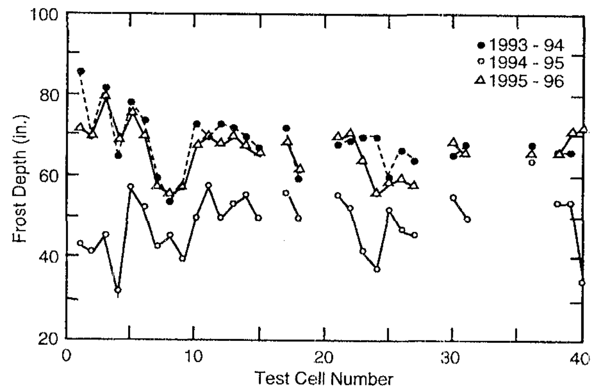

Figure 3. Maximum frost depths measured during three winters at Mn/ROAD.

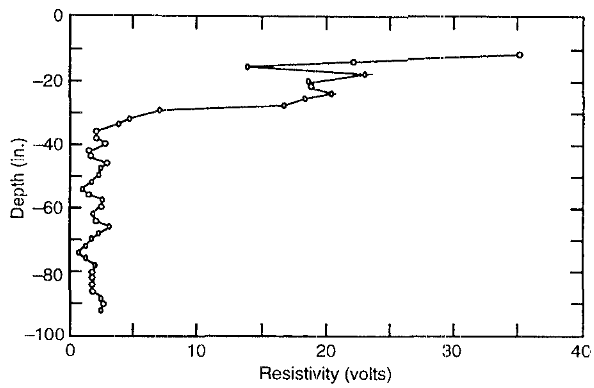

Figure 4. Electrical resistivity gauge data from Test Cell 14 on January 25, 1995.

at Mn/ROAD does not freeze at the normal freezing point of bulk water. Figure 5 (Bigl and Berg 1996b) illustrates the unfrozen water content versus sub-freezing temperature for several Mn/ROAD materials. All of the subgrade materials contain 6% to 11% by dry weight of unfrozen water at a temperature of about –1.1°C (30°F). Data in Table 6 indicate that the total moisture content of the fine-grained subgrade materials at Mn/ROAD ranged from 14.2% to 18.5% by dry weight. These two pieces of information suggest that about one-third to three-fourths of the total water in the subgrade is probably unfrozen at –1.1°C (30°F).

Determining the location of the frozen boundary using the electrical resistivity gauge data was much more difficult in the granular subgrade material than in the clayey silt subgrade. Therefore the measured values for the test cells underlain by the granular subgrade may be in error. Mn/ROAD researchers should reevaluate the measured depths for the granular subgrade.

* Personal communication, R.T. Atkins, Atkins Associates, West Lebanon, New Hampshire, 1997.

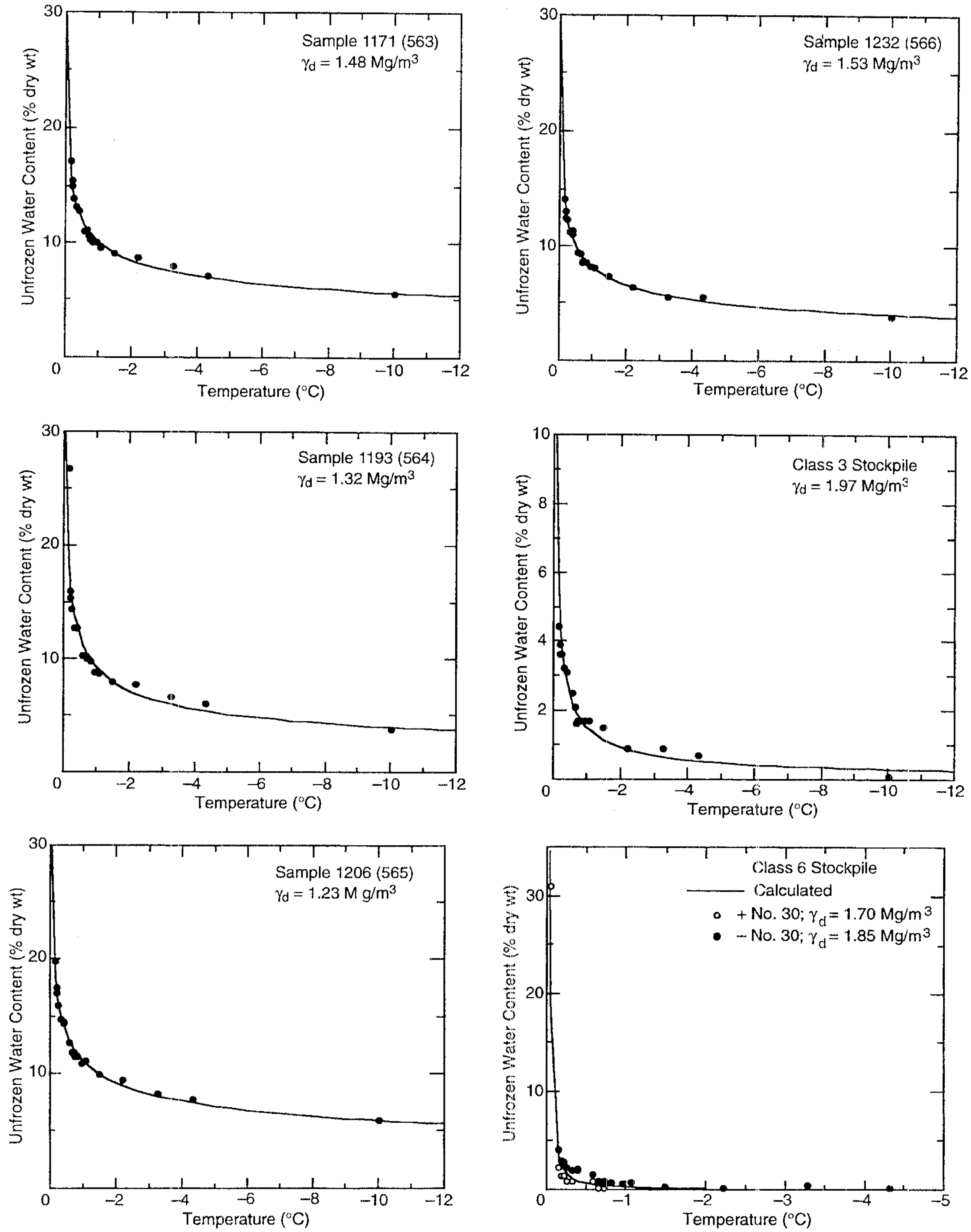

Figure 5. Temperature vs gravimetric unfrozen water content curves for four subgrade samples and two granular materials from Mn/ROAD. Solid lines represent calculated values to approximate the data.

CALCULATED FROST DEPTHS

Material and layer properties

Prior to computing frost penetration beneath the test cells at Mn/ROAD it was necessary to determine the following for each layer in each test cell:

- thickness
- soil type (coarse or fine-grained)
- dry unit weight
- gravimetric moisture content

The thickness of each layer was obtained from Minnesota Department of Transportation (1991) and is the "design thickness" value. Although the construction controls at Mn/ROAD were greater than those on a normal road construction project, it is likely that not all portions of every test cell were built to the design thickness. A sensitivity study, described in the next section, was conducted to evaluate probable errors in frost penetration depths due to varying thickness of the pavement and base course layers.

Density and moisture content data for each layer were obtained by MN/DOT from core samples obtained after materials were placed and compacted, but prior to paving. The data were incorporated into the Mn/ROAD database shortly after the samples were analyzed. The database was quizzed by Mn/ROAD researchers who provided tabulated data for this project. Appendices A and B contain data which were supplied for this study. The final column in each appendix contains the average value of moisture content or density which I determined for each layer. Note that often the database did not provide the same number of test specimens for both the density and moisture content.

Table 3. Thermal and physical properties of surface layer for each test cell.

Cell	*Thickness (in.)*	*Density (lb/ft^3)*	*Thermal conductivity (Btu/ft hr °F)*	*Heat capacity (Btu/ft^3 °F)*	*Test group*
1	5.75	138	1.08	30	5 yr ML, AC
2	5.75	138	1.08	30	5 yr ML, AC
3	5.75	138	1.08	30	5 yr ML, AC
4	8.75	138	1.08	30	5 yr ML, AC
5	7.50	145	1.25	28	5 yr ML, PCC
6	7.50	145	1.25	28	5 yr ML, PCC
7	7.50	145	1.25	28	5 yr ML, PCC
8	7.50	145	1.25	28	5 yr ML, PCC
9	7.50	145	1.25	28	5 yr ML, PCC
10	9.50	145	1.25	28	10 yr ML, pCC
11	9.50	145	1.25	28	10 yr ML, PCC
12	9.50	145	1.25	28	10 yr ML, PCC
13	9.50	145	1.25	28	10 yr ML, PCC
14	10.75	138	1.08	30	10 yr ML, AC
15	10.75	138	1.08	30	10 yr ML, AC
16	7.75	138	1.08	30	10 yr ML, AC
17	7.75	138	1.08	30	10 yr ML, AC
18	7.75	139	1.08	30	10 yr ML, AC
19	7.75	138	1.08	30	10 yr ML, AC
20	7.75	138	1.08	30	10 yr ML, AC
21	7.75	138	1.08	30	10 yr ML, AC
22	7.75	138	1.08	30	10 yr ML, AC
23	8.75	138	1.08	30	10 yr ML, AC
24	3.00	138	1.08	30	LVR, AC
25	5.00	138	1.08	30	LVR, AC
26	6.00	138	1.08	30	LVR, AC
27	3.00	138	1.08	30	LVR, AC
28	3.00	138	1.08	30	LVR, AC
29	5.00	138	1.08	30	LVR, AC
30	5.00	138	1.08	30	LVR, AC
31	3.00	138	1.08	30	LVR, AC
32	0.50	138	1.08	30	LVR, AGG
33					
34					
35	0.50	138	1.08	30	LVR, AGG
36	6.00	145	1.25	28	LVR, PCC
37	6.00	145	1.25	28	LVR, PCC
38	6.00	145	1.25	28	LVR, PCC
39	6.00	145	1.25	28	LVR, PCC
40	7/5.5/7	145	1.25	28	LVR, PCC

Note: Blank space indicates layer was not present.
1 in. = 25.4 mm; 1 lb/ft^3 = 16.0 kg/m^3; 1 Btu/ft hr °F = 1.7 W/m °C;
1 Btu/ft^3 °F = 53.7 J/m^3 °C.

Tables 3–6 provide the layer properties for each test cell; the density and moisture content data are average values for each test cell in Appendices A and B. Table 3 is for the surface course, Table 4 the base course, Table 5 the subbase course, and Table 6 the subgrade. In addition to the layer thick-

Table 4. Thermal and physical properties of base course layer for each test cell.

Cell	*Type*	*Thickness (in.)*	*Density (lb/ft^3)*	*Moisture content (%)*	*Thermal conductivity (Bru/ft hr °F)*	*Heat capacity (Btu/ft^3 °F)*	*Latent heat of fusion (Btu/ft^3)*
1	Class 4 spl	33	129.2	8.5	2.35	30.2	1581
2	6	4	130.9	6.0	2.01	28.1	1131
3	5	4	132.9	6.5	2.24	29.1	1244
4		0					
5	4	3	129.4	8.0	2.29	29.8	1491
6	4	5	128.5	8.9	2.38	30.4	1647
7	OGB	4	127.9	7.8	2.15	29.2	1437
8	OGB	4	126.6	8.4	2.16	29.5	1531
9	OGB	4	129.8	8.3	2.36	30.1	1551
10	OGB	4	129.8	8.0	2.31	29.9	1495
11	5	5	134.0	8.1	2.62	30.9	1563
12	5	5	138.7	6.7	2.68	30.5	1338
13	5	5	134.0	8.1	2.62	30.9	1563
14		0					
15		0					
16	3	28	126.3	7.6	2.02	28.7	1382
17	3	28	125.3	7.4	1.94	28.3	1335
18	6	12	129.6	6.8	2.09	28.6	1269
19	3	28	128.8	7.4	2.14	29.0	1372
20	3	28	129.7	7.2	2.16	29.1	1345
21	5	23	134.8	6.5	2.35	29.5	1262
22	6	18	131.1	5.9	2.01	28.1	1114
23	OGB	4	131.7	8.2	2.48	30.5	1555
24	6	4	130.6	4.6	1.72	26.7	865
25		0					
26		0					
27	6	11	132.1	6.4	2.16	28.8	1217
28	5	13	136.9	6.8	2.56	30.3	1340
29	4	10	129.8	7.9	2.29	29.8	1477
30	3	12	127.5	6.6	1.94	28.0	1212
31	5	4	132.9	7.2	2.36	29.8	1378
32	1C	12	133.8	8.0	2.59	30.8	1541
33	1F	12	128.2	9.0	2.36	30.4	1662
34	1F	12	127.9	7.6	2.12	29.0	1400
35	1C	12	136.8	7.7	2.75	31.2	1517
36	5	5	138.7	6.1	2.54	29.9	1218
37	5	12	136.7	7.4	2.69	30.8	1457
38	5	5	132.6	6.3	2.18	28.8	1203
39	5	5	138.7	6.7	2.68	30.5	1338
40	5	5	132.8	6.9	2.30	29.4	1320

Note: Blank space indicates layer was not present.
1 in. = 25.4 mm; 1 lb/ft^3 = 16.0 kg/m^3; 1 Btu/ft^3 = 29.8 J/m^3; 1 Btu/ft hr °F =2.7 W/m °C;
1 Btu/ft^3 °F = 53.7 J/m^3 °C.

ness, density and moisture content, the tables contain the thermal properties used for the frost depth calculations for the 93–94, 94–95 and 95–96 winters. Thermal properties in these tables are not necessarily those used in the sensitivity studies because the moisture content and density were varied in some of the sensitivity studies.

For each test cell the "design" thickness of the pavement, base course and subbase courses was input to the Modified Berggren Equation (MBE).

Table 5. Thermal and physical properties of subbase course layer for each test cell.

Cell	*Type*	*Thickness (in.)*	*Density (lb/ft^3)*	*Moisture content (%)*	*Thermal conductivity (Btu/ft hr °F)*	*Heat capacity (Btu/ft^3 °F)*	*Latent heat of fusion (Btu/ft^3)*
2	Class 4 spl	28	128.5	8.9	2.38	30.4	1647
3	3	33	127.5	7.2	2.04	28.6	1322
5	3	27	130.1	7.2	2.19	29.1	1349
7	4	3	128.5	8.9	2.38	30.4	1647
8	4	3	128.5	8.9	2.38	30.4	1647
9	4	3	128.5	8.9	2.38	30.4	1647
10	4	3	128.5	8.9	2.38	30.4	1647
18	3	9	129	7.;2	2.12	28.9	1338
23	4	3	128.5	8.9	2.38	30.4	1647
31	3	12	129	7.3	2.14	29.0	1356

Note: Unlisted layers were not present.
1 in. = 25.4 mm; 1 lb/ft^3 = 26.0 kg/m^3; 1 Btu/ft^3 = 29.8 J/m^3; 1 Btu/ft hr °F = 1.7 W/m °C;
1 Btu/ft^3 °F = 53.7 J/m^3 °C.

Thermal properties are determined in the computer program, but the values can be modified by the user. In some of the sensitivity studies, one or more of the thermal properties were altered, depending on the study.

In nearly all cases, frost penetrated below the base or subbase course layers and into the subgrade. For the MBE solutions, a subgrade layer 300 mm (1 ft) thick was generally chosen as the first subgrade layer, and if this layer did not contain the seasonal frost, 600-mm- (2-ft) thick layers were added. When the thickness of a particular layer was greater than necessary to contain the frost, the computer program used successive approximations until a "satisfactory solution" was obtained. A "satisfactory solution" for the MBE is attained when the computed cumulative freezing index is within ±5.6 °C-days (10 °F-days) of the surface freezing index. This generally results in an "approximate" frost depth which is within ±15 mm (0.6 in.) of the "exact" value.

Sensitivity studies

Preliminary investigations involved a series of sensitivity studies to illustrate the impact of important parameters in the Modified Berggren Equation (MBE) and to determine whether parameters to be used in the frost depth calculations for the three years should be "biased" to better estimate measured frost depths. A total of six sensitivity studies were made; the variables, the range of each variable studied, and the number of simulations for each variable are illustrated in Table 7.

The 94–95 winter was used in all of the sensitivity studies, and the 95–96 winter was also used in the n-factor sensitivity study.

Table 8 gives the results of the sensitivity study examining the effect of the n-factor on calculated frost depths. As anticipated, larger n-factors caused larger surface freezing indexes and resulted in greater calculated frost penetration depths. Figure 6 presents the computed frost depths as a percentage of the measured frost depths for the two winters. In all cases except Cell 24, which contains a granular subgrade, the calculated frost depths were less than 90% of the measured depths when the higher n-factors were used. When the lower n-factors were used, the calculated values were less than 80% of the measured values. These results indicated that the higher n-factors provide calculated frost depths closer to measured values and should be used in subsequent calculations. Frost depths in the "High n-factor" column of Table 8 for the 94–95 winter are used as the "standard" values for comparison in the other sensitivity studies.

Table 9 contains results of the sensitivity study on the effect of different densities on computed frost depths. The n-factors for flexible and rigid pavements were 0.90 and 0.95, respectively. The density was changed ±80 kg/m^3 (±5 lb/ft^3) from the values used in the standard calculations in Table 9. In all cases the higher density materials caused calculated frost depths to be greater than those for the standard density or the lower density. Figure 7 illustrates the effects of changing the density as

Table 6. Thermal and physical properties of subgrade layer for each test cell.

Cell	*Type (R-value)*	*Density (lb/ft³)*	*Moisture content (%)*	*Thermal conductivity (Btu/ft hr °F)*	*Heat capacity (Btu/ft³ °F)*	*Latent heat of fusion (Btu/ft³)*
1	12	109.4	16.3	1.25	32.0	2568
2	12	110.0	14.8	1.19	30.9	2344
3	12	108.8	15.4	1.19	31.1	2413
4	12	111.1	16.6	1.31	32.7	2656
5	12	112.4	15.6	1.31	32.3	2525
6	12	110.8	15.4	1.25	31.6	2457
7	12	111.1	15.5	1.26	31.8	2480
8	12	111.2	14.9	1.24	31.3	2386
9	12	111.7	15.2	1.26	31.7	2445
10	12	110.6	14.2	1.18	30.6	2262
11	12	111.3	14.3	1.20	30.9	2292
12	12	110.6	14.2	1.18	30.6	2262
13	12	111.3	14.3	1.20	30.9	2292
14	12	111.7	14.3	1.21	31.0	2300
15	12	110.5	16.0	1.28	32.0	2546
16	12	108.2	16.3	1.21	31.6	2540
17	12	109.5	18.5	1.36	33.8	2917
18	12	109.0	15.3	1.19	31.0	2402
19	12	111.6	15.4	1.28	31.9	2475
20	12	109.0	16.3	1.24	31.9	2558
21	12	111.4	15.6	1.28	32.0	2502
22	12	111.5	14.9	1.24	31.4	2392
23	12	109.6	15.3	1.21	31.2	2415
24	70	121.9	7.6	1.79	27.7	1334
25	70	121.2	7.8	1.79	27.7	1361
26	12	112.3	16.1	1.32	32.7	2604
27	12	111.1	15.8	1.28	32.1	2528
28	12	110.9	14.7	1.21	31.1	2348
29	12	112.6	15.4	1.30	32.1	2497
30	12	113.3	15.0	1.30	32.0	2447
31	12	113.1	15.9	1.35	32.7	2590
32	12	111.1	14.7	1.22	31.1	2352
33	12	110.1	16.9	1.30	32.7	2679
34	12	113.4	15.7	1.35	32.6	2564
35	12	112.8	14.9	1.29	31.8	2420
36	70	120.6	9.5	1.96	29.1	1650
37	70	120.4	9.1	1.91	28.7	1578
38	12	109.9	15.7	1.24	31.6	2485
39	12	110.7	16.7	1.31	32.7	2662
40	12	110.8	15.5	1.25	31.7	2473

1 lb/ft^3 = 16.0 kg/m^3; 1 Btu/ft^3 = 29.8 J/m^3; 1 Btu/ft hr °F = 1.7 W/m °C; 1 Btu/ft^3 °F = 53.7 J/m^3 °C.

Table 7. Summary of sensitivity studies conducted during this research.

Variable	*Range*	*No. of solutions*
n-factor	0.70–0.90 AC 0.75–0.95 PCC	10
Moisture content	Base, subbase and subgrade increased to 100% saturation and decreased same amount	12
Density	Base, subbase and subgrade ±80 kg/m^3 (5 lb ft^3)	10
Layer thickness	Pav't ±25 mm (1 in.) Base ±50 mm (2 in.) Subbase ±50 mm (2 in.)	10
Thermal conductivity	+25%	5
Mean annual temp	9.4°C or 11.1°C 49.0°F or 51.9°F	5

Note: Test cells 38, 11, 24, 30 and 17 were used in all simulations.

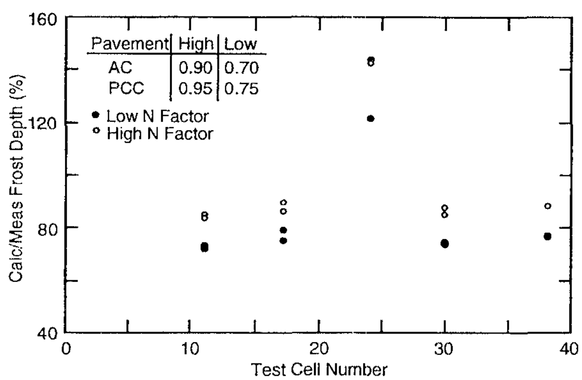

Figure 6. Sensitivity of calculated maximum frost penetration to n-factor.

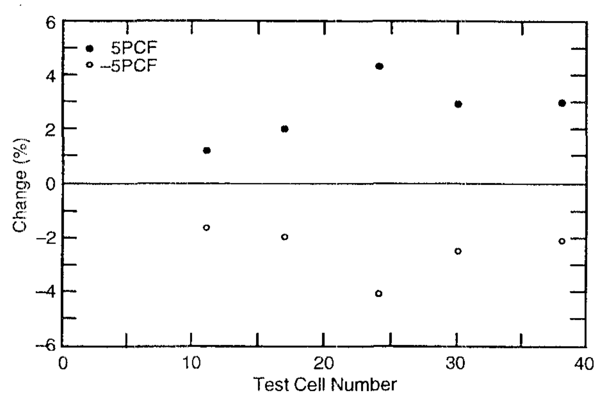

Figure 7. Sensitivity of calculated maximum frost penetration to density of base and subgrade. Changes are from the "standard" calculated value.

Table 8. Sensitivity of calculated maximum frost penetration to n-factor.

	Frost penetration (in.)			
	94–95		*95–96*	
Test cell	*Low n-factor*	*High n-factor*	*Low n-factor*	*High n-factor*
38	41.0	47.4	50.6	58.1
11	41.8	48.4	51.2	59.0
24	54.5	64.6	67.8	79.5
30	40.9	47.8	50.8	58.4
17	44.5	50.1	52.3	59.3

1 in. = 25.4 mm.

Table 9. Sensitivity of calculated maximum frost penetration to density of base and subgrade.

Test cell	*Property*	*Units*	*Low density*		*High density*		*Standard*
			Base	*Subgrade*	*Base*	*Subgrade*	
38	Density	lb/ft^3	128	105	138	115	
	k	BTU/ft hr °F	1.51	0.88	2.00	1.12	
	C	BTU/ft^3 °F	27.7	30.2	29.9	33.1	
	L	BTU/ft^3	1158	2372	1248	2598	
	X	ft		46.3		48.8	47.4
11	Density	lb/ft^3	129	106	139	116	
	k	BTU/ft hr °F	1.82	0.85	2.42	1.09	
	C	BTU/ft^3 °F	29.8	29.5	32.1	32.2	
	L	BTU/ft^3	1505	2189	1621	2395	
	X	ft		47.6		49.0	48.4
24	Density	lb/ft^3	126	117	136	127	
	k	BTU/ft hr °F	1.2	1.25	1.59	1.65	
	C	BTU/ft^3 °F	25.7	26.5	27.7	28.8	
	L	BTU/ft^3	832	1279	898	1389	
	X	ft		61.9		67.4	64.6
30	Density	lb/ft^3	123	108	133	118	
	k	BTU/ft hr °F	1.35	0.92	1.78	1.18	
	C	BTU/ft^3 °F	26.9	30.6	29.1	33.4	
	L	BTU/ft^3	1164	2339	1259	2555	
	X	ft		46.6		49.2	47.8
17	Density	lb/ft^3	120	105	130	115	
	k	BTU/ft hr °F	1.35	0.97	1.79	1.22	
	C	BTU/ft^3 °F	27.1	32.3	29.4	35.4	
	L	BTU/ft^3	1282	2783	1388	3050	
	X	ft		49.1		51.1	50.1

1 lb/ft^3 = 16.0 kg/m^3; 1 Btu/ft hr °F = 1.7 W/m °C; 1 Btu/ft^3 °F =53.7 J/m^3 °C;
1 Btu/ft^3 = 29.8 J/m^3; 1 ft = 0.3 m.

Table 10. Sensitivity of calculated maximum frost penetration to moisture content of base and subgrade.

Test cell	*Property*	*Units*	*Low moisture*		*High moisture*		*Standard*
			Base	*Subgrade*	*Base*	*Subgrade*	
38	Moist cont.	%	2	12	11	20	
	k	BTU/ft hr °F	0.91	0.82	2.39	1.14	
	C	BTU/ft^3 °F	24.4	28.3	33.2	34.9	
	L	BTU/ft^3	363	1852	2043	3118	
	X (n = 0.95)	ft		47.1		46.7	47.4
11	Moist cont.	%	6	10	10	19	
	k	BTU/ft hr °F	1.76	0.75	2.41	1.15	
	C	BTU/ft^3 °F	28.8	26.9	33.0	34.8	
	L	BTU/ft^3	1158	1539	1968	3045	
	X (n = 0.95)	ft		50.5		45.8	48.4
24	Moist cont.	%	1	1	11	15	
	k	BTU/ft hr °F	0.60	0.48	2.35	2.15	
	C	BTU/ft^3 °F	23.2	21.6	33.4	34.2	
	L	BTU/ft^3	188	176	2144	2598	
	X (n = 0.90)	ft		61.3		60.9	64.6
30	Moist cont.	%	1	12	12	18	
	k	BTU/ft hr °F	0.67	0.90	2.19	1.17	
	C	BTU/ft^3 °F	23.0	29.3	33.0	34.6	
	L	BTU/ft^3	257	1938	2166	2948	
	X (n = 0.90)	ft		42.0		47.8	47.8
17	Moist cont.	%	2	17	13	20	
	k	BTU/ft hr °F	0.81	1.03	2.14	1.14	
	C	BTU/ft^3 °F	23.4	32.7	33.1	35.0	
	L	BTU/ft^3	397	2696	2273	3138	
	X (n = 0.70)	ft		40.1		44.6	
	X (n = 0.90)	ft		44.8		50.8	50.1

1 Btu/ft hr °F = 1.7 W/m °C; 1 Btu/ft^3 °F =53.7 J/m^3 °C;
1 Btu/ft^3 =29.8 J/m^3; 1 ft = 0.3 m.

compared to the "standard" depths in Table 8. The conclusions reached from this study were that a change of ±80 kg/m³ (5 lb/ft³) will cause:

1. A ± 1 to 3% change in computed frost depths in test cells underlain by the clayey silt subgrade
2. A ± 4 to 5% change in the computed frost depths in test cells underlain by the sandy subgrade

Table 10 contains data on the effect of changing moisture contents in the base and subgrade layers. Altering the moisture contents results in changes in the thermal conductivity, k, the volumetric heat capacity, C, and the volumetric latent heat of fusion, L. For a particular base, subbase or subgrade layer, there is a decrease in all three properties when the moisture content decreases and an increase when the moisture content increases. Since changes in the values of k and L have opposite effects on calculated frost depths, one cannot generalize about the effect of changing the moisture content on the resulting computed frost depth. This is evidenced by the data in Table 10. In some cases a decrease in moisture content resulted in decreased calculated frost depth and in other cases the opposite was true. Increasing the moisture content caused similar mixed results. Figure 8 illustrates differences between the high and low water contents and the standard data in Table 8. Most of the differences are less than ± 10% of the standard frost depth.

Table 11 shows the effects of changing the pavement thickness by ±25 mm (1 in.) and changing the base course thickness by ±50 mm (2 in.). Increasing or decreasing the thickness by these amounts resulted in very minor changes in computed frost depths. In nearly all cases the differences were less than 25 mm (1 in.). Figure 9 illustrates that the differences for all except two cases are less than ±1.5% of the standard data in Table 8. I concluded from this study that a change in the thickness of the pavement or base course will have a very small impact on the depth of frost penetration. The primary reason for this finding is that most of the frost penetration is in the subgrade layer, so changes in the upper layers have little effect on the computed frost depth.

All of the calculations to this point indicated that the calculated frost depths were generally less than the measured values. Therefore, two additional sensitivity studies were conducted to bias the computed frost depths to be greater. These two studies:

Table 11. Sensitivity of calculated maximum frost penetration to thickness of pavement and base course.

Test cell	*Decrease thickness*	*Increase thickness*	*Standard depth*
38	46.9	48.0	47.4
11	47.5	48.9	48.4
24	65.3	62.9	64.6
30	47.7	47.9	47.8
17	49.6	50.8	50.1

Pavement thickness changed by 1 in.
Base course thickness changed by 2 in.
1994–95 winter used in all calculations.
n-factors 0.90 for flexible pavements and 0.95 for rigid pavements.
Frost depth in inches (1 in. = 25.4 mm).

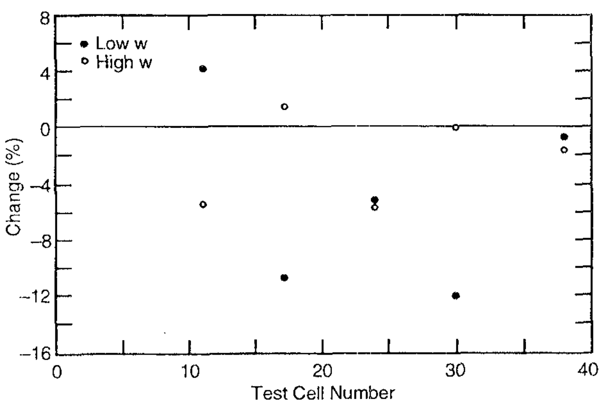

Figure 8. Sensitivity of calculated maximum frost penetration to moisture content of base and subgrade. Changes are from the "standard" calculated value.

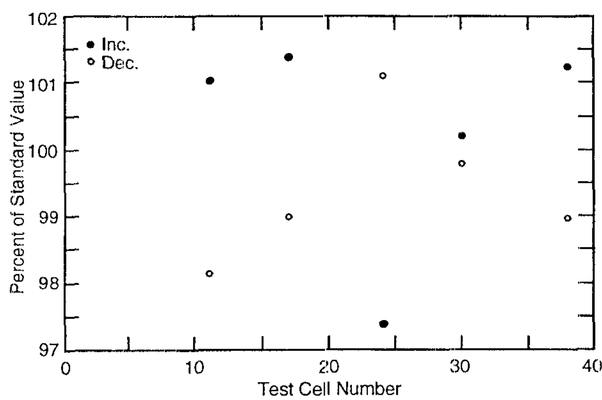

Figure 9. Sensitivity of calculated maximum frost penetration to thickness of pavement and base course. Changes are from the "standard" calculated value.

Table 12. Sensitivity of calculated maximum frost penetration to 25% increase in thermal conductivity.

Test cell	*Standard* k	*Increased* k
38	47.4	53.2
11	48.4	53.5
24	64.6	72.6
30	47.8	53.0
17	50.1	54.8

1994–95 winter used in all calculations.
n-factors 0.90 for flexible pavements and 0.95 for rigid pavements.
Standard values from Table 8 using high n-factors.
Frost depths in inches (1 in. = 25.4 mm).

1. Increased the thermal conductivity by 25%
2. Decreased the mean annual temperature from 11.1°C (51.9°F) to 9.4°C (49.0°F)

Table 12 shows the result of increasing the thermal conductivity of the pavement, base course and subgrade by 25%. As expected, all of the calculated frost depths increased from the standard values in Table 8. Figure10 indicates that the increase was on the order of 10% in the fine-grained subgrade and about 20% in the granular subgrade.

Results from the final sensitivity study are contained in Table 13 and Figure 11. The data indicate that in all cases, decreasing the MAT increased the frost penetration depth. By using the combination of high n-factors, 25% greater thermal conductivity and lower MAT, the computed frost depths for four of the five test cells were within ±3% of the

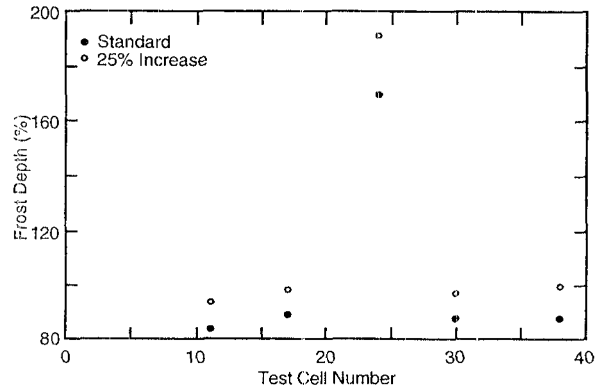

Figure 10. Sensitivity of calculated maximum frost penetration to 25% increase in the thermal conductivity of each layer. Changes are from the "standard" calculated value.

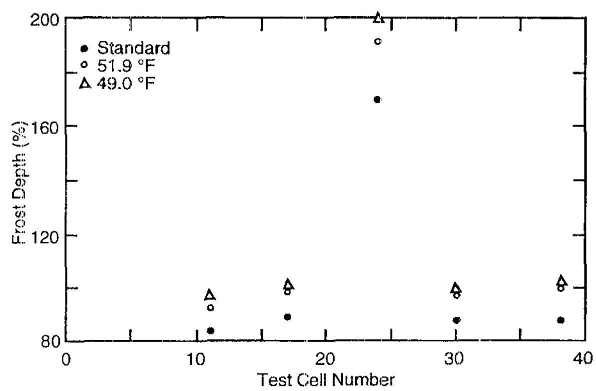

Figure 11. Sensitivity of calculated maximum frost penetration to decrease in the mean annual soil temperature (MAT). Changes are from the "standard" calculated value.

Table 13. Sensitivity of calculated maximum frost penetration to decrease in mean annual soil temperature (MAT).

	Frost depth				*Percent of measured*		
Cell	*Measured*	*Standard*	*MAT = 51.9°F*	*MAT = 49.0°F*	*Standard*	*MAT = 51.9°F*	*MAT = 49.0°F*
38	54	47.4	53.2	55.5	87.8	98.5	102.8
11	58	48.4	53.5	56.5	83.4	92.2	97.4
24	38	64.6	72.6	76.0	170.0	191.0	200.0
30	55	47.8	53	55.5	86.9	96.4	100.9
17	56	50.1	54.8	56.8	89.5	97.9	101.4

Notes: Thermal conductivity of the pavement, base course and subgrade increased by 25% for the MAT = 51.9°F and MAT = 49.0°F calculations.
1994–95 winter used in all calculations.
n-factors 0.90 for flexible pavements and 0.95 for rigid pavements.
Standard values from Table 8.
Frost depths in inches (1 in. = 25.4 mm).

measured values for the 94–95 winter. The exception was again Cell 24 with the granular subgrade. Using these three parameters to compute frost depths in Cell 24 resulted in the calculated value being about double the measured value.

The overall conclusions from these sensitivity studies were:

- Small variations in layer thickness will have a very minor effect on computed frost depth and can reasonably be neglected.
- Reasonable variations in moisture content and density of the various base course, subbase course and subgrade layers will have a minor effect, usually less than 10%, on calculated frost penetration depths.
- Use n-factors of 0.90 and 0.95, respectively, for flexible and rigid pavements.
- Multiply Kersten's calculated thermal conductivity values for the pavement, base course, subbase course and subgrade by 1.25.
- Use a mean annual temperature of 9.4°C (49°F) in the frost depth calculations.

The author's experience has been that the Modified Berggren Equation generally provides a conservative estimate of frost penetration depth. That is, it usually produces frost depths that are 5 to 20% greater than depths measured with temperature sensors. When using temperature sensors to determine frost penetration depth, the freezing point of bulk water, 0°C (32°F), is nearly always used to determine the "freezing front." Frost depths obtained from electrical resistivity gauges will generally be less than those estimated from temperature sensors because a substantial amount of the pore water must be frozen before the gauges indicate that condition. This infers that the temperature of the material "just frozen" as indicated by the electrical resistivity gauges is lower than that of bulk water. Therefore, frost depths obtained from electrical resistivity gauges will not be as great as those obtained from temperature sensors, assuming that the soil water freezes at 0°C (32°F). The magnitude of the difference in "measured" frost depths will vary depending on the temperature gradient. Steep temperature gradients, i.e. rapid heat flow, will result in relatively small differences between the two methods, but small temperature gradients may result in larger differences between the two methods.

Data from Atkins (1979) are plotted in Figure

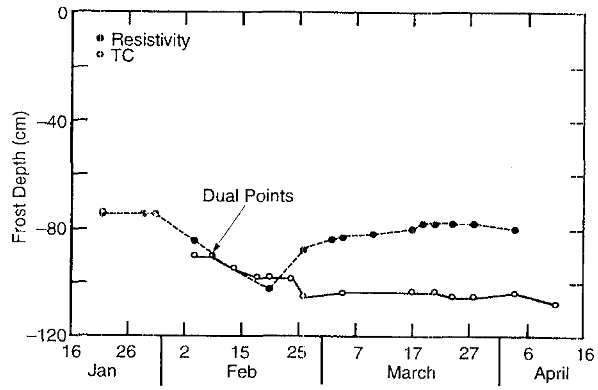

Figure 12. Frost penetration depths with time from electrical resistivity gauge data and thermocouple data, assuming a freezing point of 0°C (32°F).

12 to illustrate differences between the two frost depth measurement techniques. Relatively early in the season when the frost is penetrating rapidly into the soil (rapid heat flow and steep temperature gradients), measured frost depths from the two devices are nearly equal. Later in the winter when the frost depth is relatively stable (low heat flow and shallow temperature gradients), the difference in frost depth between the two methods is approximately 200 mm (8 in.). The soil used in Atkins' work was a silt, which probably contained less unfrozen water than the fine-grained subgrade soil at Mn/ROAD. Therefore, we would anticipate larger differences in frost depth measurements between the two devices in the Mn/ROAD test cells which incorporate the fine-grained subgrade and smaller differences in those containing the granular subgrade.

A comparison of temperature, electrical resistivity gauge data and unfrozen moisture content has not been made at Mn/ROAD. Such a study would be valuable in explaining the correlation among these three parameters at Mn/ROAD as well as the performance of the pavements during the winter and spring.

Simulations for three winters

After the sensitivity studies were completed and results analyzed, the "production" simulations were completed. Results from the sensitivity studies indicated that the following should be used in all simulations for the 93–94, 94–95 and 95–96 winters:

- A mean annual temperature of 9.4°C (49°F)

Table 14. Calculated and measured maximum frost depths (in.) for each test cell during the 1993–94 winter.

Freezing index	2057°F-days (1°C = 1.8°F)
Length of season	127 days
Begin	5 Nov 93
End	12 Mar 94

Cell	*Meas*	*Calc*	*Calc/Meas (%)*	*Cell*	*Meas*	*Calc*	*Calc/Meas (%)*
1	86	70.2	81.6	21	68	66.2	97.4
2	70	70.7	101.0	22	69	63.8	92.5
3	82	70.7	86.2	23	70	60.3	86.1
4	65	57.3	88.2	24	70	87.0	124.3
5	78	71.5	91.7	25	60	85.3	142.2
6	74	63.1	85.3	26	67	58.6	87.5
7	60	63.5	105.8	27	64	63.3	98.9
8	54	64.1	118.7	28		65.6	
9	58	64.0	110.3	29		63.1	
10	73	64.3	88.1	30	65	63.2	97.2
11	70	63.5	90.7	31	68	65.3	96.0
12	73	64.1	87.8	32		66.7	
13	72	63.5	88.2	33		64.3	
14	70	58.2	83.1	34		65.8	
15	67	57.5	85.8	35		67.5	
16		66.3		36	68	86.4	127.1
17	72	63.8	88.6	37		88.9	
18	60	64.4	107.3	38	66	63.0	95.5
19		67.6		39	66	59.8	90.6
20		66.6		40		63.7	

1 in. = 25.4 mm.

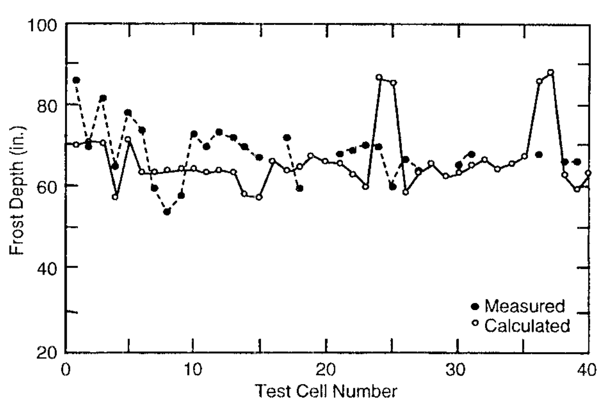

Figure 13. Calculated and measured maximum frost depths for each test cell during the 1993–94 winter.

- A multiple of 1.25 times the "baseline" thermal conductivity for all materials
- n-factors of 0.90 and 0.95 for flexible and rigid pavements, respectively

These values were in fact used in all of the production simulations for the three winters.

Table 14 contains calculated and measured frost depths for the 93–94 winter. Measurements were not available for all 40 cells, but calculations were made for all of them. Figure 13 contains the calculated and measured values for the same winter and Figure 14 contains the calculated depths as a percentage of the measured depths. The calculated values exceeded the measured values by the largest amounts in the cells with the granular subgrade (Cells 24, 25, 36 and 37). These results are consistent with findings in the sensitivity studies.

In all test cells except those with the granular subgrade, calculated frost depths were within ±20% of the measured depths and most were within ±10%. In most cells, the calculated values were less than the measured depths. The measured frost depth in Cell 1 exceeded the calculated value by the largest amount of all of the cells with the fine-grained subgrade. The reasons for these differences are not clear. Calculated frost depths exceeded measured values by the largest amounts in Cells

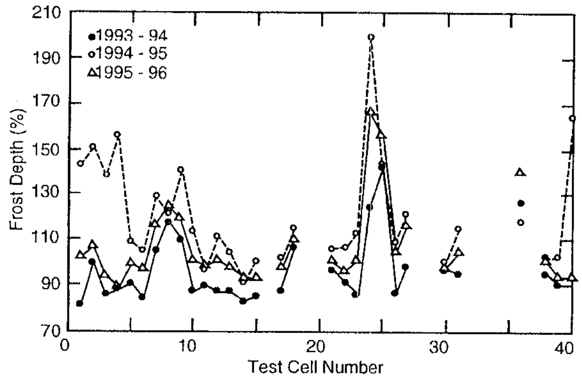

Figure 14. Calculated maximum frost depths as a percentage of measured maximum frost depths for each of the three winters.

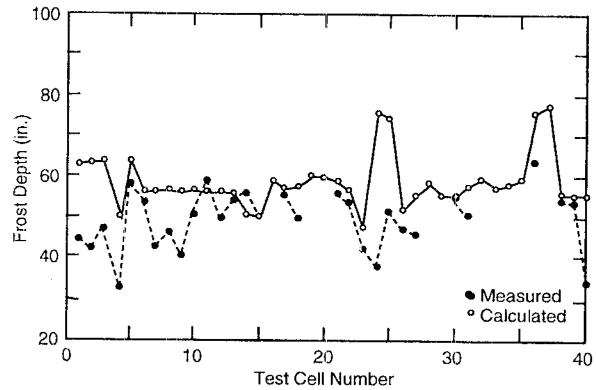

Figure 15. Measured and calculated maximum frost depths during the 1994–95 winter.

7, 8, 9 and 18. Again, reasons for the differences are not clear. However, all four of these test cells contain side drains, and Cells 7, 8 and 9 are PCC-surfaced cells containing open-graded base materials and are designed for a 5-year life. Cell 18 is an AC-surfaced cell designed for a 10-year life. The calculated frost depths for other cells with open-graded bases and/or side drains were generally less than the measured values. Perhaps these data indicate that some side drains are functioning better than others. A study of moisture sensor data from the cells might prove interesting, but is not within the scope of this project.

Table 15 and Figure 15 contain a comparison

Table 15. Calculated and measured maximum frost depths (in.) for each test cell during the 1994–95 winter.

Freezing index	1611°F-days (1°C = 1.8°F)
Length of season	109 days
Begin	21 Nov 94
End	10 Mar 95

Cell	*Meas*	*Calc*	*Calc/Meas (%)*	*Cell*	*Meas*	*Calc*	*Calc/Meas (%)*
1	44	63.2	143.6	21	56	59.2	105.7
2	42	63.3	150.7	22	53	56.7	107.0
3	46	63.7	138.5	23	42	47.3	112.6
4	32	50.1	156.6	24	38	76.0	200.0
5	58	63.8	110.0	25	52	74.4	143.1
6	53	55.7	105.1	26	47	51.7	110.0
7	43	56.0	130.2	27	46	55.8	121.3
8	46	56.4	122.6	28		58.2	
9	40	56.4	141.0	29		55.6	
10	50	56.8	113.6	30	55	55.5	100.9
11	58	56.5	97.4	31	50	57.8	115.6
12	50	56.2	112.4	32		59.5	
13	54	56.5	104.6	33		57.3	
14	56	51.0	91.1	34		58.1	
15	50	50.1	100.2	35		60.0	
16		59.0		36	64	75.7	118.3
17	56	57.0	101.8	37		77.6	
18	50	57.6	115.2	38	54	55.5	102.8
19		60.1		39	54	55.4	102.6
20		59.9		40	34	56.0	164.7

1 in. = 25.4 mm.

of calculated and measured frost depths for the 94–95 winter. An interesting note is that during this winter the vast majority of the calculated frost depths were greater than the measured values. During the 93–94 winter, on the other hand, most of the calculated frost depths were less than the measured values. The freezing index for the 93–94 winter was 1143 °C-days (2057 °F-days) but during the 1994–95 winter it was only 895 °C-days (1611 °F-days). For most test cells both calculated and measured frost penetration depths were greater during the 93–94 winter than during the 94–95 winter.

In all except Cells 11 (a PCC-surfaced cell with no side drain) and 14 (a full depth AC section) the computed values were larger than the measured frost depths. The greatest difference was in Cell 24, which was underlain by a granular subgrade. None of the computed frost depths were less than 118% of the measured depths in cells containing granular subgrades.

Calculated frost depths were 138% to 157% of the measured frost depths in Cells 1–4. The water table is very high in this area since a pond abuts the roadway embankment along this section of the road. Measured frost depths in these cells were significantly less than in most other cells during this winter.

Since nearly all of the computed frost depths are greater than the measured depths, it is possible that the surface n-factors were lower this winter than in the 93–94 winter. Another possibility is that the moisture content of the subgrade increased, causing the measured frost depth to be slightly lower than expected.

Air temperatures were lower during the 95–96 winter than in either of the previous two. The freezing index was 1344 °C-days (2419 °F-days), which was about 50% colder than the 94–95 winter and nearly 20% colder than the 93–94 winter. Figure 3 indicates that the frost depths in the 93–94 and 95–96 winters were about the same, but in most instances those in the 93–94 winter were slightly greater. Again the possibilities of increased sub-

Table 16. Calculated and measured maximum frost depths (in.) for each test cell during the 1995–96 winter.

Freezing index	2419 °F-days (1°C = 1.8°F)
Length of season	158 days
Begin	2 Nov 95
End	8 Apr 96

Cell	*Meas*	*Calc*	*Calc/Meas (%)*	*Cell*	*Meas*	*Calc*	*Calc/Meas (%)*
1	72	74.8	103.9	21	70	71.1	101.6
2	70	75.5	107.9	22	71	69.0	97.2
3	80	75.8	94.8	23	64	65.0	101.6
4	69	62.0	89.9	24	56	94.1	168.0
5	76	76.4	100.5	25	59	92.2	156.3
6	70	68.2	97.4	26	60	63.7	106.2
7	58	68.5	118.1	27	58	68.0	117.2
8	56	69.5	124.1	28		70.4	
9	58	69.5	119.8	29		68.2	
10	68	69.4	102.1	30	69	67.9	98.4
11	70	69.2	98.9	31	66	70.1	106.2
12	68	69.0	101.5	32		71.3	
13	70	69.2	98.9	33		69.4	
14	68	63.1	92.8	34		70.9	
15	66	61.8	93.6	35		72.0	
16		70.8		36	66	93.3	141.4
17	69	68.2	98.8	37		96.0	
18	62	69.1	111.5	38	66	67.8	102.7
19		72.1		39	71	67.7	95.4
20		71.2		40	72	68.4	95.0

1 in. = 25.4 mm.

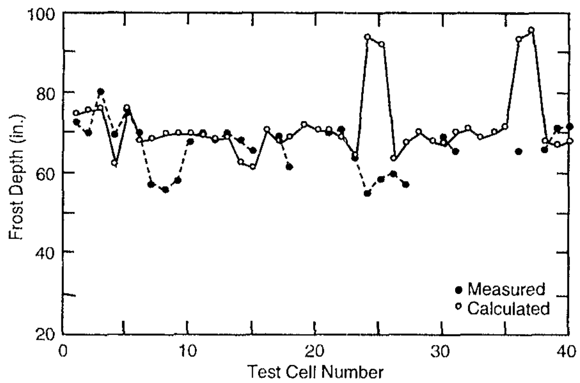

Figure 16. Measured and calculated maximum frost depths during the 1995–96 winter.

grade moisture contents during 95–96 or decreased surface n-factors arise as possible explanations for the differences.

Table 16 and Figure 16 compare calculated and measured maximum frost penetration depths during the 95–96 winter. Once again computed frost depths in the test cells containing the granular subgrade are substantially greater than the measured depths. The average difference is greater than 150%.

For nearly all of the other test cells, measured and calculated frost depths agree within about ±10%. Exceptions are Cells 7, 8 and 9, again, and Cells 18 and 27. Cell 18 contains a side drain and is a 10-yr design life AC cell, and 27 is a low volume road AC-surfaced cell with no side drain.

Calculated frost depths for Cells 7, 8 and 9 were greater than measured depths for all three years, indicating to me that the n-factors, moisture contents, thermal properties or layer thicknesses are incorrect in the calculations. Determining which parameter or parameters are incorrect is beyond the scope of this project, but should be pursued to explain these discrepancies.

Table 17 contains a summary of all of the computed frost depths as compared to the measured depths. Also contained in the table are the maximum, minimum and average differences as well as the standard deviation of the ratios. Table 18 contains similar data for only the test cells underlain by the fine-grained subgrade. The maximum differences are considerably lower, but the minimum values remain the same, as expected. The average values are reduced and the standard devi-

Table 17. Calculated maximum frost depths as a percentage of measured maximum depths for all test cells.

	Calc/Meas (%)				*Calc/Meas (%)*		
Cell	*93–94*	*94–95*	*95–96*	*Cell*	*93–94*	*94–95*	*95–96*
1	81.6	143.6	103.9	23	86.1	112.6	101.6
2	101.0	150.7	107.9	24	124.3	200.0	168.0
3	86.2	138.5	94.8	25	142.2	143.1	156.3
4	88.2	156.6	89.9	26	87.5	110.0	106.2
5	91.7	110.0	100.5	27	98.9	121.3	117.2
6	85.3	105.1	97.4	28			
7	105.8	130.2	118.1	29			
8	118.7	122.6	124.1	30	97.2	100.9	98.4
9	110.3	141.0	119.8	31	96.0	115.6	106.2
10	88.1	113.6	102.1	32			
11	90.7	97.4	98.9	33			
12	87.8	112.4	101.5	34			
13	88.2	104.6	98.9	35			
14	83.1	91.1	92.8	36	127.1	118.3	141.4
15	85.8	100.2	93.6	37			
16				38	95.5	102.8	102.7
17	88.6	101.8	98.8	39	90.6	102.6	95.4
18	107.3	115.2	111.5	40		164.7	95.0
19				Max	142.2	200.0	168.0
20				Min	81.6	91.1	89.9
21	97.4	105.7	101.6	Avg	97.4	121.3	108.0
22	92.5	107.0	97.2	Std dev	14.7	24.1	18.3

Table 18. Calculated maximum frost depths as a percentage of measured maximum depths for test cells underlain by fine-grained subgrade.

	Calc/Meas (%)				Calc/Meas (%)		
Cell	93–94	94–95	95–96	Cell	93–94	94–95	95–96
1	81.6	143.6	103.9	23	86.1	112.6	101.6
2	101.0	150.7	107.9	24			
3	86.2	138.5	94.8	25			
4	88.2	156.6	89.9	26	87.5	110.0	106.2
5	91.7	110.0	100.5	27	98.9	121.3	117.2
6	85.3	105.1	97.4	28			
7	105.8	130.2	118.1	29			
8	118.7	122.6	124.1	30	97.2	100.9	98.4
9	110.3	141.0	119.8	31	96.0	115.6	106.2
10	88.1	113.6	102.1	32			
11	90.7	97.4	98.9	33			
12	87.8	112.4	101.5	34			
13	88.2	104.6	98.9	35			
14	83.1	91.1	92.8	36			
15	85.8	100.2	93.6	37			
16				38	95.5	102.8	102.7
17	88.6	101.8	98.8	39	90.6	102.6	95.4
18	107.3	115.2	111.5	40		164.7	95.0
19				Max	118.7	156.6	124.1
20				Min	81.6	91.1	89.9
21	97.4	105.7	101.6	Avg	93.5	117.7	102.8
22	92.5	107.0	97.2	Std dev	9.1	19.5	8.7

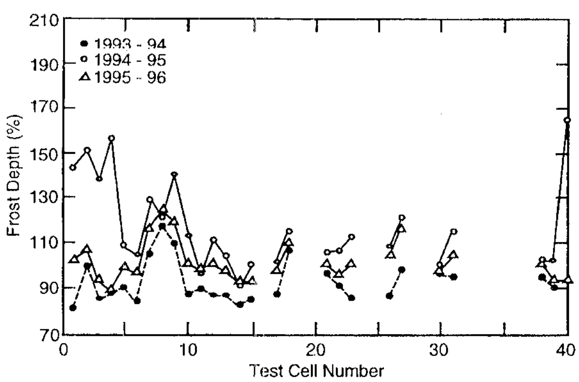

Figure 17. Calculated maximum frost depths as a percentage of measured maximum frost depths for test cells with a fine-grained subgrade.

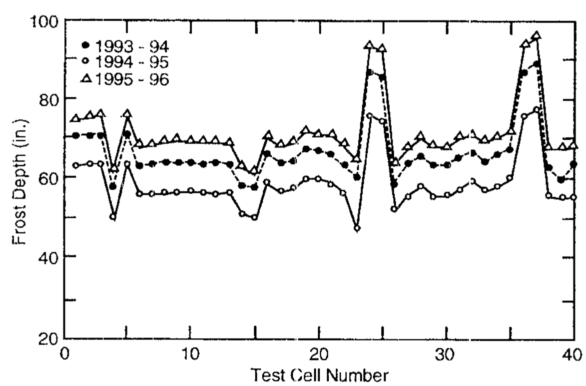

Figure 18. Calculated maximum frost depths for each of the test cells for each of the three winters.

ations are substantially reduced, by more than 50% in the 95–96 winter.

Figure 17 displays the frost depths shown in Table 18. The largest differences are for Cells 1–10 during the 94–95 winter. In this group only Cells 5 and 6 have differences less than 110%. Cells 1–4, 7 and 9 are greater than 130%. Possible reasons for the differences were discussed above. Differences between the calculated and measured frost depths were greatest for the 94–95 winter, which was the warmest of the three winters.

Figure 18 contains the calculated frost depths for each of the test cells for each of the winters. The data are "consistent" in that the warmest winter (94–95) provided the shallowest depths and the coldest winter (95–96) provided the greatest depths. For the calculations, the only parameters that were changed from year to year were the magnitude of the freezing index and the length of the freezing season. As expected, the shallowest frost depths each year were in the full-depth asphalt–concrete-surfaced test cells and the greatest were beneath the cells underlain by the granular subgrade.

To obtain an estimate of the "average" error between the calculated and measured frost depths, the average measured frost depth was obtained by adding all of the measured depths and dividing by the number of observations. The average error was obtained by calculating the difference between the calculated and measured depths, squaring the difference, summing the squares, dividing by the number of observations, and finally taking the square root of that number.

The average error for all of the cells where frost depths were measured was 18.92%, but when only the cells underlain by the fine-grained subgrade were used the average error reduced to 13.26%. There were a total of 89 values for all of the cells, and 80 values when only the cells underlain by the fine-grained subgrade were used.

Measured and calculated data for all of the test cells where frost depths were measured were plotted and a linear regression applied to the data (Fig. 19). The "line of equality" is plotted on the figure as well as the regression line and ±95% confidence levels. The equation resulting from the linear regression is:

$$Y = 42.9701 + 0.3624X \tag{4}$$

where Y is the calculated frost depth (in.) and X is the measured frost depth (in.).

The standard error of estimate for this data set is 5.12 in. Reviewing the data in Figure 19 indicated that all eight "outliers" on the high side of the 95% confidence limit were from test cells containing the granular subgrade. This result was not surprising because all of the calculated frost depths for cells underlain by the granular subgrade were greater than measured depths by over 150%.

The data from test cells underlain by the granular subgrade were removed and a regression conducted on the remaining data. The results are shown in Figure 20. Again the graph contains the "line of equality" as well as the regression line and the ±95% confidence limits. The regression equation for this set of data is:

$$Y = 38.0107 + 0.4055X \tag{5}$$

where the parameters are as defined for Equation 4. The standard error of estimate for these data is 2.92, slightly more than half of the value for all the data.

When all of the data are considered, the average error in the calculated frost depths ranged from $(5.12/86) \times 100 = 6.0\%$ to $(5.12/32) \times 100 = 16.2\%$, depending on the measured frost depth. When data from the cells containing the granular subgrade are omitted, the errors reduce to $(2.92/86) \times 100 = 3.4\%$ to $(2.92/32) \times 100 = 9.1\%$ of the measured values.

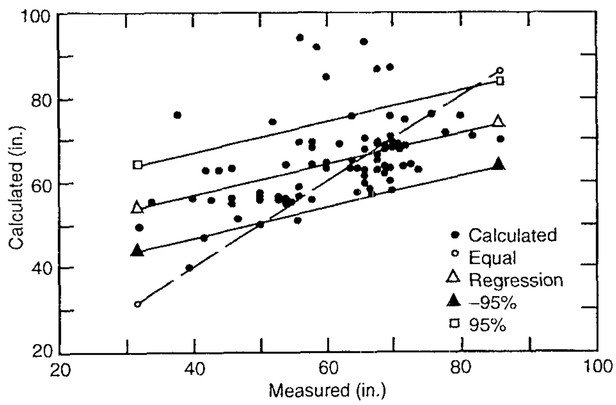

Figure 19. Comparison of measured and calculated maximum frost depths for all test cells, with regression lines and line of equality.

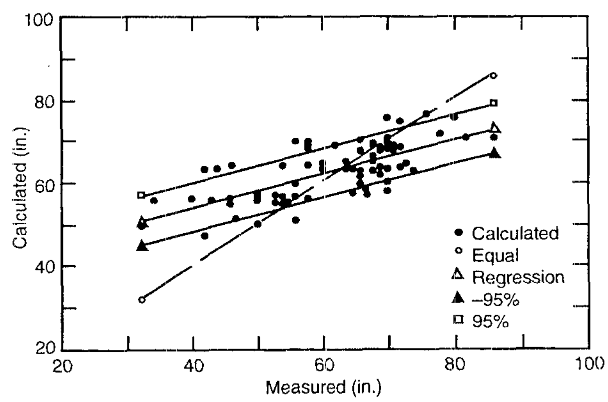

Figure 20. Comparison of measured and calculated maximum frost depths for test cells on fine-grained subgrade only, with regression lines and line of equality.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions developed from the sensitivity studies included:

- Small variations in layer thickness will have a very minor effect on computed frost depth and can reasonably be neglected
- Reasonable variations in moisture content and density of the various base course, subbase course and subgrade layers will have a minor effect, usually less than 10%, on calculated frost penetration depth
- Larger n-factors caused deeper calculated frost penetration depths; the use of n-factors of 0.90 and 0.95, respectively, for flexible and rigid pavements provided the most reasonable estimates of frost depth
- Increasing the thermal conductivity of the materials by 25% resulted in closer agreement between calculated and measured frost depths
- Using a mean annual soil temperature of 9.4°C (49.0°F) rather than 11.1°C (51.9°F) resulted in better agreement between calculated and measured data

When these data were used in the Modified Berggren Equation to calculate frost depths, the calculated depths were generally within ±18.9% of the measured depths. When the test cells containing only the fine-grained subgrade were considered, the majority of the calculated depths were within ±13.3% of the measured depths.

Frost depth calculations were consistent from year to year. However, the computed frost depths were not consistent with the measured frost depths from year to year. The measured frost depths were generally greatest during the 93–94 winter, although it was not as cold as the 95–96 winter. These differences may have been due to increased moisture contents in the base and subgrade during the latter two years, due to changes in the surface n-factors or other reasons. Data which might have explained the differences were not part of this study. Two studies should be initiated at Mn/ROAD to explain, at least in part, the differences:

- Evaluate changes in subsurface moisture contents, especially in the freezing zone beneath each test cell, during the three years
- Install instruments to measure pavement surface temperatures in at least some of the test cells

The character of individual winters can cause differences in measured frost depths even though the freezing index values may be the same. For example, two winters having the same freezing index could occur by one having moderately low temperatures for the entire winter and another having a very cold beginning followed by a thaw followed by another cold spell. The Modified Berggren Equation would provide the same maximum frost depth, but measured values could be considerably different. A computer program which calculates subsurface temperatures and frost penetration depths on a daily basis could probably much more closely approximate the actual measured values than the MBE. Two programs which have this capability are the FROST program developed at the U. S. Army's Cold Regions Research and Engineering Laboratory (Guymon, Berg and Hromadka 1993) and the Federal Highway Administration's Environmental Effects Model (EEM) (Lytton et al. 1989).

All of the calculated frost depths in test cells underlain by the granular subgrade were much larger than the measured values. Calculated frost depths in the test cells underlain by the granular subgrade were also greater than those in the cells underlain by the fine-grained subgrade. This situation was expected, based upon moisture contents in the two types of subgrades. Mn/ROAD scientists should carefully reevaluate frost depth measurements in cells underlain by the granular subgrade. If the measured depths are correct, an explanation of why the measured values are so small must be sought. Two potential explanations are: substantial increase in moisture content of the granular subgrade or very low thermal conductivity of the granular subgrade.

Since frost and thaw depths and rates are important in explaining the performance of test cells at Mn/ROAD, MN/DOT should explore the possibility of measuring the thermal conductivity of several of the pavement, base course, subbase course and subgrade materials. Two possible sources for these measurements are the University of Minnesota and the Cold Regions Research and Engineering Laboratory. Both of these organizations had equipment to measure the thermal conductivity of wet soils a few years ago. I do not know whether either of them have the capability now.

The overall performance of test cells containing subsurface drains and drainage layers should be compared with that at similar test cells containing no drainage materials. Of particular interest are moisture contents in the base and subgrade materials and rutting and/or cracking at the pavement surface.

A comparison of frost penetration depths as indicated by the electrical resistivity gauge data, the subsurface temperature data and the time domain reflectometry data should be made. A detailed study of these data will indicate amounts of unfrozen moisture at various temperatures, the temperatures at which the subgrade soils begin to freeze, and the response of the electrical resistivity gauges to different moisture contents and different materials. More accurate "measurements" of frost depth, as interpreted from the electrical resistivity gauges, should result.

Samples of the subgrade soils should be obtained and sent to CRREL, or some other laboratory, to determine the unfrozen water content versus temperature curves similar to those in Figure 5. The subgrade materials used in the prior CRREL tests (Bigl and Berg 1996b) were obtained from test pits during the initial exploration for Mn/ROAD and may not be representative of the materials actually used. The results from the proposed laboratory tests could be compared to the unfrozen moisture content versus subsurface temperature data obtained from the TDR and temperature data in the field. Either type of unfrozen moisture content versus temperature data could be used in more comprehensive frost penetration models such as the FROST program or the EEM mentioned above.

The amount of unfrozen moisture in the soil will significantly affect the frost penetration as well as the strength of the soil. As stated at the end of the *Measured Frost Depths* section of this report, data from Figure 5 and Table 6 indicate that 25% to 75% of the moisture in the subgrade soil may be unfrozen at a temperature of –1.1°C (30°F). To illustrate the approximate impact of unfrozen moisture on frost depth, eight additional simulations were made with the Modified Berggren Equation; the results are contained in Table 19. These eight simulations illustrate the extreme effects of considering unfrozen moisture content in the Modified Berggren Equation. In the first set of four solutions the latent heat of the subgrade was reduced to 75% of its original value, and in the second set of four solutions the latent heat of the subgrade was reduced to 25% of the original value. Decreasing the latent heat of fusion of the subgrade to 75% of its original value caused the calculated frost depth to be increased by about 10%. Decreasing the latent heat of fusion of the subgrade to 25% of its original value caused the calculated frost depths to be increased by approximately 50%. From these few computations it is evident that effects of unfrozen water in the subgrade can cause substantial changes in the calculated frost depths. The impact of this parameter may be greater than changing

Table 19. Sensitivity of calculated maximum frost penetration to reduction in latent heat of fusion of fine-grained subgrade.

	Frost depth (in.)					*Percent of measured*			
Cell	*Meas*	*Std*	*1.00 L*	*0.75 L*	*0.25 L*	*Std*	*1.00 L*	*0.75 L*	*0.25 L*
38	54	47.4	55.5	61.2	81.8	87.8	102.8	113.3	151.5
11	58	48.4	56.5	61.5	82.0	83.4	97.4	106.0	141.4
24	38	64.6							
30	55	47.8	55.5	60.7	83.6	86.9	100.9	110.4	152.0
17	56	50.1	56.8	61.3	83.0	89.5	101.4	109.5	148.2

Notes:
Thermal conductivity of the pavement, base course and subgrade increased by 25% for the calculations
1994–95 winter used in all calculations
MAT = 49.0°F (9.4°C) in all calculations
n-factors 0.90 for flexible pavements and 0.95 for rigid pavements
Standard values from Table 8
1 in. = 25.4 mm

the mean annual temperature or increasing the thermal conductivity of the pavement, base, subbase and subgrade materials.

When some test cells are totally reconstructed, one or more temperature assemblies should be installed which extend to a depth of at least 6.1 m (20 ft). These assemblies could provide reasonable subsurface temperature data for modeling depths greater than 2.4 m (8 ft) for all of the test cells.

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APPENDIX A: MN/ROAD SOIL DENSITY DATA FROM CONSTRUCTION RECORDS

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
1	1	AC	5.75	5.75		
1	2	CL4S	33.00	5.75	128.52	
1	2	CL4S	33.00	8.75	131.04	
1	2	CL4S	33.00	11.75	129.15	
1	2	CL4S	33.00	17.75	129.78	
1	2	CL4S	33.00	23.75	129.78	
1	2	CL4S	33.00	26.75	128.52	
1	2	CL4S	33.00	29.75	131.04	
1	2	CL4S	33.00	32.75	126.63	
1	2	CL4S	33.00	35.75	128.52	129.2
1	2	CL4S	33.00	38.75		
1	3	SG12	192.00	38.75	111.78	
1	3	SG12	192.00	44.75	107.10	
1	3	SG12	192.00	45.95	107.10	
1	3	SG12	192.00	50.75	110.65	
1	3	SG12	192.00	55.55	109.24	
1	3	SG12	192.00	56.75	110.31	109.4
2	1	AC	5.75	5.75		
2	2	CL6S	4.00	5.75	130.88	130.9
2	3	CL4S	28.00	11.75	127.89	
2	3	CL4S	28.00	17.75	129.78	
2	3	CL4S	28.00	21.75	129.15	
2	3	CL4S	28.00	27.75	127.26	128.5
2	3	CL4S	28.00	37.75	112.29	
2	3	CL4S	28.00	44.95	109.56	
2	3	CL4S	28.00	46.15	109.18	
2	3	CL4S	28.00	49.75	111.18	
2	3	CL4S	28.00	56.95	108.17	
2	3	CL4S	28.00	58.15	112.46	
2	4	SG12	192.00	37.75	112.29	
2	4	SG12	192.00	44.95	109.56	
2	4	SG12	192.00	46.15	109.18	
2	4	SG12	192.00	49.75	111.18	
2	4	SG12	192.00	56.95	108.17	
2	4	SG12	192.00	58.15	112.46	110.5
3	1	AC	5.75	5.75		
3	2	CL5S	4.00	5.75	127.81	
3	2	CL5S	4.00	8.75	138.01	132.9
3	2	CL5S	4.00	9.75	127.18	
3	3	CL3S	33.00	9.75	127.18	
3	3	CL3S	33.00	16.75	127.18	
3	3	CL3S	33.00	20.75	127.18	
3	3	CL3S	33.00	26.75	128.43	
3	3	CL3S	33.00	32.75	127.81	127.5
3	3	CL3S	33.00	42.75	111.73	
3	3	CL3S	33.00	49.95	109.18	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
3	3	CL3S	33.00	51.15	107.06	
3	3	CL3S	33.00	54.75	107.10	
3	4	SG12	192.00	42.75	111.73	
3	4	SG12	192.00	49.95	109.18	
3	4	SG12	192.00	51.15	107.06	
3	4	SG12	192.00	54.75	107.10	108.8
4	1	AC	8.75	8.75		
4	2	SG12	192.00	8.75	112.96	
4	2	SG12	192.00	14.75	114.24	
4	2	SG12	192.00	15.95	110.31	
4	2	SG12	192.00	24.35	109.24	
4	2	SG12	192.00	25.55	113.40	
4	2	SG12	192.00	26.75	113.93	
4	2	SG12	192.00	32.75	110.31	
4	2	SG12	192.00	35.15	111.38	
4	2	SG12	192.00	38.75	113.12	
4	2	SG12	192.00	45.95	108.17	
4	2	SG12	192.00	47.15	107.10	
4	2	SG12	192.00	50.75	111.38	
4	2	SG12	192.00	54.35	108.58	111.1
5	1	PCC	7.50	7.50		
5	2	CL4S	3.00	7.50	129.41	129.4
5	2	CL4S	3.00	10.50		
5	3	CL3S	27.00	10.50	130.31	
5	3	CL3S	27.00	16.50	128.43	
5	3	CL3S	27.00	21.00	130.31	
5	3	CL3S	27.00	22.50	130.94	
5	3	CL3S	27.00	28.50	130.31	130.1
5	3	CL3S	27.00	37.50	113.40	
5	3	CL3S	27.00	43.50	115.36	
5	3	CL3S	27.00	45.90	115.36	
5	3	CL3S	27.00	47.10	108.17	
5	3	CL3S	27.00	53.10	110.73	
5	3	CL3S	27.00	54.30	111.80	
5	3	CL3S	27.00	55.50	110.73	
5	3	CL3S	27.00	56.70	108.12	
5	3	CL3S	27.00	62.70	115.36	
5	3	CL3S	27.00	63.90	117.83	
5	4	SG12	192.00	37.50	113.40	
5	4	SG12	192.00	43.50	115.36	
5	4	SG12	192.00	45.90	115.36	
5	4	SG12	192.00	47.10	108.17	
5	4	SG12	192.00	53.10	110.73	
5	4	SG12	192.00	54.30	111.80	
5	4	SG12	192.00	55.50	110.73	
5	4	SG12	192.00	56.70	108.12	
5	4	SG12	192.00	62.70	115.36	
5	4	SG12	192.00	63.90	117.83	
5	4	SG12	192.00	72.30	107.50	112.4

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
6	1	PCC	7.50	7.50		
6	2	CL4S	5.00	7.50	128.52	128.5
6	2	CL4S	5.00	12.50		
6	3	SG12	192.00	12.50	111.85	
6	3	SG12	192.00	19.70	111.77	
6	3	SG12	192.00	23.30	109.18	
6	3	SG12	192.00	29.30	106.00	
6	3	SG12	192.00	30.50	111.30	
6	3	SG12	192.00	37.70	115.92	
6	3	SG12	192.00	46.10	110.09	
6	3	SG12	192.00	47.30	107.50	
6	3	SG12	192.00	48.50	111.80	
6	3	SG12	192.00	54.50	112.30	110.8
7	1	PCC	7.50	7.50		
7	2	PASB	4.00	7.50	127.89	127.9
7	3	CL4S	3.00	14.50	114.19	
7	4	SG12	192.00	14.50	114.19	
7	4	SG12	192.00	24.10	108.12	
7	4	SG12	192.00	25.30	107.06	
7	4	SG12	192.00	26.50	116.48	
7	4	SG12	192.00	27.70	106.00	
7	4	SG12	192.00	32.50	108.17	
7	4	SG12	192.00	34.90	111.30	
7	4	SG12	192.00	37.30	113.12	
7	4	SG12	192.00	42.10	114.24	
7	4	SG12	192.00	45.70	112.30	
7	4	SG12	192.00	60.10	111.38	
7	4	SG12	192.00	62.50	109.24	
7	4	SG12	192.00	63.70	109.65	
7	4	SG12	192.00	64.90	110.31	111.1
8	1	PCC	7.50	7.50		
8	2	PASB	4.00	7.50	126.63	
8	3	CL4S	3.00	14.50		
8	4	SG12	192.00	14.50	113.87	
8	4	SG12	192.00	21.70	106.00	
8	4	SG12	192.00	31.30	112.00	
8	4	SG12	192.00	32.50	113.12	
8	4	SG12	192.00	36.10	116.48	
8	4	SG12	192.00	39.70	109.18	
8	4	SG12	192.00	43.30	107.06	
8	4	SG12	192.00	45.70	113.12	
8	4	SG12	192.00	50.50	113.12	
8	4	SG12	192.00	51.70	110.24	
8	4	SG12	192.00	54.10	113.12	
8	4	SG12	192.00	57.70	111.71	
8	4	SG12	192.00	60.10	108.17	
8	4	SG12	192.00	62.50	107.50	
8	4	SG12	192.00	63.70	112.55	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
8	4	SG12	192.00	66.10	112.00	111.2
9	1	PCC	7.50	7.50		
9	2	PASB	4.00	7.50	129.78	129.8
9	3	CL4S	3.00	14.50		
9	4	SG12	192.00	14.50	113.12	
9	4	SG12	192.00	20.50	114.24	
9	4	SG12	192.00	24.10	116.48	
9	4	SG12	192.00	26.50	109.24	
9	4	SG12	192.00	30.10	109.18	
9	4	SG12	192.00	33.70	109.65	
9	4	SG12	192.00	34.90	112.00	
9	4	SG12	192.00	40.90	109.65	
9	4	SG12	192.00	42.10	115.36	
9	4	SG12	192.00	45.70	111.21	
9	4	SG12	192.00	46.90	114.80	
9	4	SG12	192.00	49.30	109.11	
9	4	SG12	192.00	51.70	115.36	
9	4	SG12	192.00	52.90	109.18	
9	4	SG12	192.00	54.10	110.85	
9	4	SG12	192.00	62.50	108.12	111.7
10	1	PCC	9.50	9.50		
10	2	PASB	4.00	9.50	129.78	129.8
10	3	CL4S	3.00	16.50		
10	4	SG12	192.00	16.50	113.49	
10	4	SG12	192.00	23.70	114.24	
10	4	SG12	192.00	24.90	110.03	
10	4	SG12	192.00	28.50	114.24	
10	4	SG12	192.00	32.10	109.24	
10	4	SG12	192.00	34.50	115.36	
10	4	SG12	192.00	35.70	109.24	
10	4	SG12	192.00	36.90	113.04	
10	4	SG12	192.00	42.90	113.12	
10	4	SG12	192.00	45.30	103.02	
10	4	SG12	192.00	48.90	108.58	
10	4	SG12	192.00	50.10	110.73	
10	4	SG12	192.00	53.70	107.06	
10	4	SG12	192.00	56.10	107.06	
10	4	SG12	192.00	58.50	110.31	110.6
10	4	SG12	192.00	59.70	112.00	112.0
11	1	PCC	9.50	9.50		
11	2	CL5S	5.00	9.50	134.03	134.0
11	2	CL5S	5.00	14.50		
11	3	SG12	192.00	14.50	113.12	
11	3	SG12	192.00	19.30	113.93	
11	3	SG12	192.00	20.50	115.18	
11	3	SG12	192.00	28.90	109.11	
11	3	SG12	192.00	31.30	104.70	
11	3	SG12	192.00	32.50	106.79	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
11	3	SG12	192.00	37.30	115.36	
11	3	SG12	192.00	38.50	112.00	
11	3	SG12	192.00	43.30	112.00	
11	3	SG12	192.00	44.50	116.48	
11	3	SG12	192.00	48.10	107.50	
11	3	SG12	192.00	49.30	109.65	
11	3	SG12	192.00	52.90	107.06	
11	3	SG12	192.00	56.50	112.88	
11	3	SG12	192.00	57.70	107.50	
11	3	SG12	192.00	60.10	120.03	
11	3	SG12	192.00	62.50	108.91	111.3
12	1	PCC	9.50	9.50		
12	2	CL5S	5.00	9.50	138.67	138.7
12	2	CL5S	5.00	14.50	110.65	
12	3	SG12	192.00	14.50	110.65	
12	3	SG12	192.00	19.30	107.06	
12	3	SG12	192.00	20.50	110.90	
12	3	SG12	192.00	27.70	105.75	
12	3	SG12	192.00	28.90	116.48	
12	3	SG12	192.00	30.10	105.75	
12	3	SG12	192.00	33.70	112.00	
12	3	SG12	192.00	36.10	114.24	
12	3	SG12	192.00	42.10	112.00	
12	3	SG12	192.00	43.30	116.48	
12	3	SG12	192.00	48.10	109.65	
12	3	SG12	192.00	50.50	109.65	
12	3	SG12	192.00	54.10	111.80	
12	3	SG12	192.00	56.50	108.94	
12	3	SG12	192.00	61.30	107.50	110.6
13	1	PCC	9.50	9.50		
13	2	CL5S	5.00	9.50	138.01	138.0
13	2	CL5S	5.00	14.50		
13	3	SG12	192.00	14.50	116.48	
13	3	SG12	192.00	19.30	109.65	
13	3	SG12	192.00	20.50	111.80	
13	3	SG12	192.00	22.90	112.88	
13	3	SG12	192.00	24.10	107.50	
13	3	SG12	192.00	25.30	109.24	
13	3	SG12	192.00	28.90	109.65	
13	3	SG12	192.00	34.90	108.00	
13	3	SG12	192.00	36.10	108.68	
13	3	SG12	192.00	38.40	110.73	
13	3	SG12	192.00	40.90	110.16	
13	3	SG12	192.00	44.50	103.28	
13	3	SG12	192.00	45.70	113.12	
13	3	SG12	192.00	49.30	113.12	
13	3	SG12	192.00	55.30	109.65	
13	3	SG12	192.00	57.70	110.73	110.3

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
14	1	AC	10.75	3.60	111.72	
14	1	AC	10.75	4.80	109.65	
14	1	AC	10.75	7.20	104.04	
14	1	AC	10.75	8.40	108.29	
14	1	AC	10.75	9.60	112.20	
14	1	AC	10.75	10.75		
14	2	SG12	192.00	10.75	111.21	
14	2	SG12	192.00	10.80	110.31	
14	2	SG12	192.00	12.00	110.85	
14	2	SG12	192.00	14.35	108.58	
14	2	SG12	192.00	14.40	117.60	
14	2	SG12	192.00	15.60	114.48	
14	2	SG12	192.00	17.95	107.50	
14	2	SG12	192.00	19.15	111.80	
14	2	SG12	192.00	20.35	108.58	
14	2	SG12	192.00	21.60	112.32	
14	2	SG12	192.00	24.00	112.32	
14	2	SG12	192.00	25.15	113.12	
14	2	SG12	192.00	26.40	108.58	
14	2	SG12	192.00	27.55	116.48	111.7
14	2	SG12	192.00	33.55	106.56	
14	2	SG12	192.00	33.60	119.33	
14	2	SG12	192.00	34.75	111.38	
14	2	SG12	192.00	37.15	104.04	
14	2	SG12	192.00	37.20	107.22	
14	2	SG12	192.00	38.40	109.08	
14	2	SG12	192.00	39.60	107.50	
14	2	SG12	192.00	40.75	113.40	
14	2	SG12	192.00	40.80	102.57	
14	2	SG12	192.00	42.00	112.82	
14	2	SG12	192.00	44.35	103.02	
14	2	SG12	192.00	46.75	102.00	
14	2	SG12	192.00	47.95	113.12	
14	2	SG12	192.00	49.15	104.04	
14	2	SG12	192.00	49.20	111.60	
14	2	SG12	192.00	51.60	113.40	
14	2	SG12	192.00	54.00	117.18	
14	2	SG12	192.00	55.15	109.65	
14	2	SG12	192.00	57.55	106.61	109.2
15	1	AC	10.75	2.40	106.26	
15	1	AC	10.75	3.60	104.04	
15	1	AC	10.75	4.80	113.30	
15	1	AC	10.75	7.20	109.08	
15	1	AC	10.75	9.60	114.48	
15	1	AC	10.75	10.75	113.81	?
15	2	SG12	192.00	10.75	113.81	
15	2	SG12	192.00	10.80	109.65	
15	2	SG12	192.00	14.40	107.47	
15	2	SG12	192.00	16.75	109.65	
15	2	SG12	192.00	16.80	113.12	110.7

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3)	
					Sample	Layer avg
15	2	SG12	192.00	20.35	107.50	
15	2	SG12	192.00	21.60	105.06	
15	2	SG12	192.00	22.75	108.58	
15	2	SG12	192.00	23.95	107.10	107.1
15	2	SG12	192.00	24.00	118.25	
15	2	SG12	192.00	28.75	114.24	
15	2	SG12	192.00	28.80	112.09	
15	2	SG12	192.00	31.20	109.71	110.5
15	2	SG12	192.00	33.55	106.08	
15	2	SG12	192.00	34.75	112.32	
15	2	SG12	192.00	36.00	106.13	
15	2	SG12	192.00	37.15	105.06	
15	2	SG12	192.00	40.75	109.08	
15	2	SG12	192.00	42.00	105.84	
15	2	SG12	192.00	45.55	103.53	
15	2	SG12	192.00	46.75	105.57	
15	2	SG12	192.00	46.80	108.58	
15	2	SG12	192.00	48.00	110.16	
15	2	SG12	192.00	49.20	103.20	
15	2	SG12	192.00	50.35	103.02	
15	2	SG12	192.00	52.75	117.60	
15	2	SG12	192.00	57.55	105.57	
15	2	SG12	192.00	58.75	108.58	
15	2	SG12	192.00	58.80	111.03	
15	2	SG12	192.00	60.00	111.38	
15	2	SG12	192.00	62.40	117.81	
15	2	SG12	192.00	66.00	114.83	
15	2	SG12	192.00	69.60	108.47	
15	2	SG12	192.00	72.00	116.64	
15	2	SG12	192.00	80.40	116.49	109.4
16	1	AC	7.75	7.75	128.43	
16	2	CL3S	28.00	7.75	128.43	
16	2	CL3S	28.00	8.40	114.24	
16	2	CL3S	28.00	11.75	125.93	
16	2	CL3S	28.00	17.75	129.69	
16	2	CL3S	28.00	23.75	129.69	
16	2	CL3S	28.00	29.75	129.69	126.3
16	2	CL3S	28.00	35.75	109.18	
16	3	SG12	192.00	35.75	109.18	
16	3	SG12	192.00	40.55		
16	3	SG12	192.00	42.95	106.08	
16	3	SG12	192.00	45.35		
16	3	SG12	192.00	46.55	114.24	
16	3	SG12	192.00	51.35	103.53	
16	3	SG12	192.00	53.75	104.04	
16	3	SG12	192.00	58.55	102.00	
16	3	SG12	192.00	63.60	110.73	
16	3	SG12	192.00	81.35	113.30	
16	3	SG12	192.00	117.35	109.65	108.2

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
17	1	AC	7.75	7.75	130.94	
17	2	CL3S	28.00	7.75	130.94	
17	2	CL3S	28.00	11.75	125.93	
17	2	CL3S	28.00	15.60	106.39	
17	2	CL3S	28.00	17.75	130.94	
17	2	CL3S	28.00	23.75	127.81	
17	2	CL3S	28.00	29.75	129.69	125.3
17	2	CL3S	28.00	35.75	113.33	
17	3	SG12	192.00	35.75	113.33	
17	3	SG12	192.00	39.35		
17	3	SG12	192.00	42.95		
17	3	SG12	192.00	44.15	113.12	
17	3	SG12	192.00	45.35	105.06	
17	3	SG12	192.00	46.55	103.02	
17	3	SG12	192.00	48.95	115.36	
17	3	SG12	192.00	50.15	103.02	109.5
17	3	SG12	192.00	63.35	107.10	
17	3	SG12	192.00	65.75	104.04	
17	3	SG12	192.00	72.95	107.64	
17	3	SG12	192.00	137.75	111.80	107.6
18	1	AC	7.75	7.75	130.63	
18	2	CL6S	12.00	7.75	130.63	
18	2	CL6S	12.00	10.75	127.18	
18	2	CL6S	12.00	13.75	129.99	129.6
18	3	CL3S	9.00	29.95	102.00	
18	3	CL3S	9.00	31.15	113.12	
18	4	SG12	192.00	29.95	102.00	
18	4	SG12	192.00	31.15	113.12	
18	4	SG12	192.00	38.35	109.18	
18	4	SG12	192.00	41.95		
18	4	SG12	192.00	44.35	113.12	
18	4	SG12	192.00	46.75	110.60	
18	4	SG12	192.00	47.95	114.24	
18	4	SG12	192.00	49.15	103.02	
18	4	SG12	192.00	50.35	114.24	
18	4	SG12	192.00	59.95	106.40	
18	4	SG12	192.00	61.15	109.76	
18	4	SG12	192.00	100.75	103.20	
18	4	SG12	192.00	113.95	108.58	
18	4	SG12	192.00	131.95	109.65	109.0
19	1	AC	7.75	7.75	128.43	
19	2	CL3S	28.00	7.75	128.43	
19	2	CL3S	28.00	11.75	130.31	
19	2	CL3S	28.00	17.75	130.31	
19	2	CL3S	28.00	23.75	128.43	
19	2	CL3S	28.00	29.75	126.55	128.8
19	2	CL3S	28.00	35.75	113.63	
19	3	SG12	192.00	35.75	113.63	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
19	3	SG12	192.00	41.75	104.04	
19	3	SG12	192.00	42.95	113.12	
19	3	SG12	192.00	48.95	110.16	
19	3	SG12	192.00	51.35		
19	3	SG12	192.00	54.95	103.02	
19	3	SG12	192.00	58.55	104.86	
19	3	SG12	192.00	60.95	113.12	
19	3	SG12	192.00	63.35	112.00	
19	3	SG12	192.00	64.55	113.12	
19	3	SG12	192.00	69.35	114.24	
19	3	SG12	192.00	75.35	113.12	
19	3	SG12	192.00	88.55	112.00	
19	3	SG12	192.00	96.95	112.88	
19	3	SG12	192.00	105.35	116.70	
19	3	SG12	192.00	111.35	114.24	
19	3	SG12	192.00	119.75	107.50	
19	3	SG12	192.00	120.95	107.52	
19	3	SG12	192.00	131.75	122.80	
19	3	SG12	192.00	165.35	109.65	111.6
20	1	AC	7.75	7.75	130.31	
20	2	CL3S	28.00	7.75	130.31	
20	2	CL3S	28.00	11.75	130.94	
20	2	CL3S	28.00	17.75	130.31	
20	2	CL3S	28.00	23.75	130.94	
20	2	CL3S	28.00	29.75	125.93	129.7
20	2	CL3S	28.00	35.75	110.54	
20	3	SG12	192.00	35.75	110.54	
20	3	SG12	192.00	36.95	109.65	
20	3	SG12	192.00	45.35		
20	3	SG12	192.00	47.75	114.24	
20	3	SG12	192.00	51.35	110.31	
20	3	SG12	192.00	52.55	108.68	
20	3	SG12	192.00	58.55	106.08	
20	3	SG12	192.00	59.75	107.64	
20	3	SG12	192.00	60.95	104.04	
20	3	SG12	192.00	64.55	114.24	
20	3	SG12	192.00	65.75	112.00	
20	3	SG12	192.00	66.95	105.06	
20	3	SG12	192.00	68.15	103.20	
20	3	SG12	192.00	70.55	106.22	
20	3	SG12	192.00	75.35	109.76	
20	3	SG12	192.00	80.15	110.88	
20	3	SG12	192.00	82.55	110.88	
20	3	SG12	192.00	86.15	107.52	
20	3	SG12	192.00	87.35	112.00	
20	3	SG12	192.00	95.75	106.40	109.0
20	3	SG12	192.00	99.35	127.79	
20	3	SG12	192.00	106.55	109.81	
20	3	SG12	192.00	113.75	129.13	
20	3	SG12	192.00	116.15	127.79	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
20	3	SG12	192.00	122.15	121.70	
20	3	SG12	192.00	123.35	110.73	
20	3	SG12	192.00	124.55	124.13	
20	3	SG12	192.00	128.15	111.80	
20	3	SG12	192.00	131.75	116.83	
20	3	SG12	192.00	144.95	119.27	
20	3	SG12	192.00	155.75	120.48	119.9
21	1	AC	7.75	7.75	136.68	
21	2	CL5S	23.00	7.75	136.68	
21	2	CL5S	23.00	12.75	138.67	
21	2	CL5S	23.00	18.75	131.27	
21	2	CL5S	23.00	24.75	132.70	134.8
21	2	CL5S	23.00	30.75	111.72	
21	3	SG12	192.00	30.75	111.72	
21	3	SG12	192.00	31.95	116.48	
21	3	SG12	192.00	40.35		
21	3	SG12	192.00	42.75		
21	3	SG12	192.00	47.55		
21	3	SG12	192.00	48.75	122.80	
21	3	SG12	192.00	49.95	104.54	
21	3	SG12	192.00	51.15	104.04	
21	3	SG12	192.00	54.75	108.64	
21	3	SG12	192.00	60.75	112.00	
21	3	SG12	192.00	65.55	109.65	
21	3	SG12	192.00	69.15	109.76	
21	3	SG12	192.00	72.75	114.24	111.4
22	1	AC	7.75	7.75	133.85	
22	2	CL6S	18.00	7.75	133.85	
22	2	CL6S	18.00	13.75	129.34	
22	2	CL6S	18.00	19.75	129.99	131.1
22	2	CL6S	18.00	25.75	113.53	
22	3	SG12	192.00	25.75	113.53	
22	3	SG12	192.00	29.35	117.60	
22	3	SG12	192.00	30.55	113.12	
22	3	SG12	192.00	32.95	111.69	
22	3	SG12	192.00	35.35	113.12	
22	3	SG12	192.00	38.95	112.00	
22	3	SG12	192.00	41.35		
22	3	SG12	192.00	43.75	113.88	
22	3	SG12	192.00	44.95	109.08	
22	3	SG12	192.00	52.15	108.00	
22	3	SG12	192.00	53.35	105.06	
22	3	SG12	192.00	55.75	113.32	
22	3	SG12	192.00	58.15	105.06	
22	3	SG12	192.00	68.95	116.48	
22	3	SG12	192.00	82.15	105.35	
22	3	SG12	192.00	84.55	113.57	111.5
22	3	SG12	192.00	94.15	117.83	
22	3	SG12	192.00	107.35	117.83	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
22	3	SG12	192.00	127.75	121.32	
22	3	SG12	192.00	133.75	119.61	
22	3	SG12	192.00	136.15	121.32	
22	3	SG12	192.00	137.35	116.29	
22	3	SG12	192.00	175.75	120.86	119.3
23	1	AC	8.75	8.75	131.67	
23	2	PASB	4.00	8.75	131.67	131.7
23	3	CL4S	3.00	15.75	113.32	
23	3	CL4S	3.00	16.95	109.65	
23	4	SG12	192.00	15.75	113.32	
23	4	SG12	192.00	16.95	109.65	
23	4	SG12	192.00	24.15	109.40	
23	4	SG12	192.00	30.15	105.06	
23	4	SG12	192.00	31.35	109.65	
23	4	SG12	192.00	34.95	110.73	
23	4	SG12	192.00	38.55		
23	4	SG12	192.00	39.75		
23	4	SG12	192.00	44.55	102.00	
23	4	SG12	192.00	46.95	111.80	
23	4	SG12	192.00	51.75	104.04	
23	4	SG12	192.00	55.35	107.50	
23	4	SG12	192.00	56.55	114.24	
23	4	SG12	192.00	62.55	118.05	109.6
24	1	AC	3.00	3.00	130.63	
24	2	CL6S	4.00	3.00	130.63	
24	2	CL6S	4.00	7.00	122.85	
24	3	SG70	192.00	7.00	122.85	
24	3	SG70	192.00	13.00	124.02	
24	3	SG70	192.00	19.00	121.68	
24	3	SG70	192.00	22.60	118.17	
24	3	SG70	192.00	25.00	124.02	
24	3	SG70	192.00	28.60	124.02	
24	3	SG70	192.00	29.80	119.34	
24	3	SG70	192.00	31.00	121.68	
24	3	SG70	192.00	32.20	120.51	
24	3	SG70	192.00	34.60	121.68	
24	3	SG70	192.00	43.00	120.51	
24	3	SG70	192.00	44.20	120.51	
24	3	SG70	192.00	45.40	127.53	
24	3	SG70	192.00	56.20	119.34	
24	3	SG70	192.00	57.40	122.85	121.9
24	3	SG70	192.00	124.40	131.23	
24	3	SG70	192.00	224.00	111.77	121.9
25	1	AC	5.00	5.00	122.39	
25	2	SG70	192.00	5.00	122.39	
25	2	SG70	192.00	11.00	124.02	
25	2	SG70	192.00	17.00	122.85	
25	2	SG70	192.00	19.40	121.68	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft³) Sample	Dry density (lb/ft³) Layer avg
25	2	SG70	192.00	20.60	119.34	
25	2	SG70	192.00	21.80	126.36	
25	2	SG70	192.00	23.00	117.00	
25	2	SG70	192.00	26.60	121.68	
25	2	SG70	192.00	29.00	122.85	
25	2	SG70	192.00	33.80	118.17	
25	2	SG70	192.00	36.20	127.53	
25	2	SG70	192.00	37.40	118.17	
25	2	SG70	192.00	43.40	120.51	
25	2	SG70	192.00	44.60	122.85	
25	2	SG70	192.00	47.00	117.00	
25	2	SG70	192.00	48.20	120.51	
25	2	SG70	192.00	54.20	121.68	
25	2	SG70	192.00	55.40	117.00	121.2
26	1	AC	6.00	6.00	114.24	
26	2	SG12	192.00	6.00	114.24	
26	2	SG12	192.00	12.00	112.00	
26	2	SG12	192.00	13.20	113.12	
26	2	SG12	192.00	19.20	112.00	
26	2	SG12	192.00	20.40	110.73	
26	2	SG12	192.00	24.00	114.91	
26	2	SG12	192.00	30.00	116.82	
26	2	SG12	192.00	36.00	115.40	
26	2	SG12	192.00	42.00	108.17	
26	2	SG12	192.00	44.40	110.31	
26	2	SG12	192.00	48.00	112.84	
26	2	SG12	192.00	60.00	112.00	
26	2	SG12	192.00	64.80	112.00	
26	2	SG12	192.00	66.00	108.64	
26	2	SG12	192.00	67.20	112.00	
26	2	SG12	192.00	76.80	110.88	112.3
27	1	AC	3.00	3.00	130.37	
27	2	CL6S	11.00	3.00	130.37	
27	2	CL6S	11.00	9.00	133.85	132.1
27	2	CL6S	11.00	14.00	112.83	
27	3	SG12	192.00	14.00	112.83	
27	3	SG12	192.00	15.20	110.24	
27	3	SG12	192.00	21.20	110.24	
27	3	SG12	192.00	22.40	113.02	
27	3	SG12	192.00	29.60	112.88	
27	3	SG12	192.00	32.00	108.17	
27	3	SG12	192.00	33.20	113.40	
27	3	SG12	192.00	38.00	108.17	
27	3	SG12	192.00	47.60	107.10	
27	3	SG12	192.00	48.80	112.00	
27	3	SG12	192.00	50.00	113.12	
27	3	SG12	192.00	68.80	115.36	
27	3	SG12	192.00	70.00	112.00	
27	3	SG12	192.00	83.20	108.38	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Layer avg
27	3	SG12	192.00	84.40	109.24	111.1
28	1	AC	3.00	3.00	138.67	
28	2	CL5S	13.00	3.00	138.67	
28	2	CL5S	13.00	7.00	134.69	
28	2	CL5S	13.00	12.00	137.35	136.9
28	2	CL5S	13.00	16.00	116.48	
28	3	SG12	192.00	16.00	116.48	
28	3	SG12	192.00	18.40	110.88	
28	3	SG12	192.00	23.20	109.74	
28	3	SG12	192.00	25.60	111.80	
28	3	SG12	192.00	30.40		
28	3	SG12	192.00	32.80	110.73	
28	3	SG12	192.00	34.00	107.50	
28	3	SG12	192.00	36.40	115.36	
28	3	SG12	192.00	37.60	109.65	
28	3	SG12	192.00	40.00	109.24	
28	3	SG12	192.00	41.20	111.18	
28	3	SG12	192.00	65.60	113.68	
28	3	SG12	192.00	71.60	109.65	
28	3	SG12	192.00	72.80	108.17	
28	3	SG12	192.00	83.60	108.77	110.9
29	1	AC	5.00	5.00	129.78	
29	2	CL4S	10.00	5.00	129.78	
29	2	CL4S	10.00	11.00	129.78	129.8
29	2	CL4S	10.00	15.00	117.38	
29	3	SG12	192.00	15.00	117.38	
29	3	SG12	192.00	21.00	116.70	
29	3	SG12	192.00	25.80	111.38	
29	3	SG12	192.00	27.00	104.70	
29	3	SG12	192.00	28.20	112.25	
29	3	SG12	192.00	30.60	110.73	
29	3	SG12	192.00	31.80	111.79	
29	3	SG12	192.00	36.60	115.36	
29	3	SG12	192.00	51.00	114.80	
29	3	SG12	192.00	51.60	117.60	
29	3	SG12	192.00	52.80	112.00	
29	3	SG12	192.00	55.20	112.00	
29	3	SG12	192.00	58.80	112.00	
29	3	SG12	192.00	63.60	115.57	
29	3	SG12	192.00	66.00	108.58	
29	3	SG12	192.00	72.00	107.52	
29	3	SG12	192.00	73.20	114.24	112.6
30	1	AC	5.00	5.00	128.43	
30	2	CL3S	12.00	5.00	128.43	
30	2	CL3S	12.00	11.00	126.55	127.5
30	2	CL3S	12.00	17.00	114.80	
30	3	SG12	192.00	17.00	114.80	
30	3	SG12	192.00	18.20	115.36	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3)	
					Sample	Layer avg
30	3	SG12	192.00	20.00	131.04	
30	3	SG12	192.00	21.80	114.24	
30	3	SG12	192.00	25.40	116.48	
30	3	SG12	192.00	26.60	112.89	
30	3	SG12	192.00	29.00	110.31	
30	3	SG12	192.00	32.60	112.00	
30	3	SG12	192.00	33.80	110.73	
30	3	SG12	192.00	39.80	110.09	
30	3	SG12	192.00	41.00	106.26	
30	3	SG12	192.00	50.40	105.35	
30	3	SG12	192.00	50.80	115.36	
30	3	SG12	192.00	52.00	112.00	
30	3	SG12	192.00	58.00	113.68	
30	3	SG12	192.00	59.20	111.80	
30	3	SG12	192.00	60.20	108.58	
30	3	SG12	192.00	65.20	111.80	
30	3	SG12	192.00	66.40	109.65	
30	3	SG12	192.00	71.20	106.43	112.4
30	3	SG12	192.00	72.40	115.36	
30	3	SG12	192.00	74.80	117.60	
30	3	SG12	192.00	77.20	123.07	113.3
31	1	AC	3.00	3.00	132.89	
31	2	CL5S	4.00	3.00	132.89	
31	3	CL3S	12.00	19.00	117.89	
31	3	CL3S	12.00	27.40	116.48	
31	3	CL3S	12.00	28.60	107.10	
31	4	SG12	192.00	19.00	117.89	
31	4	SG12	192.00	27.40	116.48	
31	4	SG12	192.00	28.60	107.10	
31	4	SG12	192.00	33.40	113.12	
31	4	SG12	192.00	34.60	114.24	
31	4	SG12	192.00	35.80	107.50	
31	4	SG12	192.00	38.20	108.17	
31	4	SG12	192.00	51.20	115.36	
31	4	SG12	192.00	59.60	116.48	
31	4	SG12	192.00	60.80	116.48	
31	4	SG12	192.00	66.80	113.68	
31	4	SG12	192.00	68.00	112.46	
31	4	SG12	192.00	77.60	107.57	
31	4	SG12	192.00	82.40	115.36	113.1
32	1	CL1C	12.00	0.00	136.76	
32	1	CL1C	12.00	6.00	136.76	
32	1	CL1C	12.00	12.00	114.80	
32	2	SG12	192.00	12.00	114.80	
32	2	SG12	192.00	19.20	111.38	
32	2	SG12	192.00	26.40	111.92	
32	2	SG12	192.00	27.60	117.60	
32	2	SG12	192.00	32.40	108.58	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
32	2	SG12	192.00	34.80	111.26	
32	2	SG12	192.00	54.00	111.79	
32	2	SG12	192.00	60.00	113.12	
32	2	SG12	192.00	62.40	111.38	
32	2	SG12	192.00	67.20	110.31	
32	2	SG12	192.00	69.60	111.38	
32	2	SG12	192.00	75.60	112.00	
32	2	SG12	192.00	76.80	108.58	
32	2	SG12	192.00	78.00	111.80	
32	2	SG12	192.00	92.40	109.76	
32	2	SG12	192.00	97.20	112.00	
32	2	SG12	192.00	102.00	110.88	
32	2	SG12	192.00	103.20	103.20	
32	2	SG12	192.00	106.80	113.12	
32	2	SG12	192.00	108.00	107.52	111.1
33	1	CL1C	12.00	0.00	132.82	
33	1	CL1C	12.00	6.00	134.79	133.8
33	1	CL1C	12.00	12.00	124.82	
33	2	SG12	192.00	12.00	124.82	
33	2	SG12	192.00	15.60	109.71	
33	2	SG12	192.00	18.00		
33	2	SG12	192.00	20.40	108.86	
33	2	SG12	192.00	22.80	110.31	
33	2	SG12	192.00	30.00	113.12	
33	2	SG12	192.00	36.00	109.78	
33	2	SG12	192.00	44.40	109.11	
33	2	SG12	192.00	46.80	114.24	
33	2	SG12	192.00	52.80	107.52	
33	2	SG12	192.00	55.20	107.52	
33	2	SG12	192.00	56.40	109.24	
33	2	SG12	192.00	58.80	113.12	
33	2	SG12	192.00	60.00	106.40	
33	2	SG12	192.00	61.20	112.00	110.1
34	1	CL1F	12.00	0.00	129.17	
34	1	CL1F	12.00	6.00	127.31	128.2
34	1	CL1F	12.00	12.00	114.91	
34	2	SG12	192.00	12.00	114.91	
34	2	SG12	192.00	16.80	111.74	
34	2	SG12	192.00	18.00	110.24	
34	2	SG12	192.00	21.60	111.38	
34	2	SG12	192.00	22.80	109.24	
34	2	SG12	192.00	27.60	107.10	
34	2	SG12	192.00	28.80	109.24	
34	2	SG12	192.00	30.00	114.24	
34	2	SG12	192.00	31.20	117.60	
34	2	SG12	192.00	42.00	119.34	
34	2	SG12	192.00	48.00	117.60	
34	2	SG12	192.00	50.40	112.00	
34	2	SG12	192.00	54.00	111.69	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
34	2	SG12	192.00	55.20	115.36	
34	2	SG12	192.00	57.60	109.24	
34	2	SG12	192.00	62.40	107.10	
34	2	SG12	192.00	63.60	113.12	
34	2	SG12	192.00	67.20	126.60	
34	2	SG12	192.00	68.40	116.48	113.4
35	1	CL1F	12.00	0.00	127.31	
35	1	CL1F	12.00	6.00	128.55	127.9
35	2	SG12	192.00	16.80	110.65	
35	2	SG12	192.00	18.00	109.24	
35	2	SG12	192.00	19.20	111.97	
35	2	SG12	192.00	20.40	114.24	
35	2	SG12	192.00	24.00	112.81	
35	2	SG12	192.00	28.80	114.24	
35	2	SG12	192.00	30.00	113.12	
35	2	SG12	192.00	36.00	107.10	
35	2	SG12	192.00	42.00	110.73	
35	2	SG12	192.00	45.60	116.48	
35	2	SG12	192.00	46.80	116.48	
35	2	SG12	192.00	52.80	107.50	
35	2	SG12	192.00	54.00	112.86	
35	2	SG12	192.00	66.00	108.38	
35	2	SG12	192.00	75.60	126.28	112.8
36	1	PCC	6.00	6.00	138.67	
36	2	CL5S	5.00	6.00	138.67	
36	2	CL5S	5.00	11.00	120.51	
36	3	SG70	192.00	11.00	120.51	
36	3	SG70	192.00	17.00	121.68	
36	3	SG70	192.00	18.20	121.68	
36	3	SG70	192.00	26.60	119.93	
36	3	SG70	192.00	29.00	121.68	
36	3	SG70	192.00	35.00	124.02	
36	3	SG70	192.00	36.20	119.73	
36	3	SG70	192.00	37.40	121.10	
36	3	SG70	192.00	38.60	120.51	
36	3	SG70	192.00	43.40	113.49	
36	3	SG70	192.00	45.80	124.02	
36	3	SG70	192.00	47.00	120.51	
36	3	SG70	192.00	48.20	119.34	
36	3	SG70	192.00	53.00	120.51	
36	3	SG70	192.00	60.20	121.68	
36	3	SG70	192.00	61.40	119.34	120.6
37	1	PCC	6.00	6.00	136.68	
37	2	CL5S	12.00	6.00	136.68	
37	2	CL5S	12.00	12.00	136.68	136.7
37	2	CL5S	12.00	18.00	120.51	
37	3	SG70	192.00	18.00	120.51	
37	3	SG70	192.00	24.00	118.17	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3) Sample	Dry density (lb/ft^3) Layer avg
37	3	SG70	192.00	32.40	120.51	
37	3	SG70	192.00	33.60	120.51	
37	3	SG70	192.00	36.00	121.68	
37	3	SG70	192.00	37.20	120.51	
37	3	SG70	192.00	43.20	121.68	
37	3	SG70	192.00	45.60	120.51	
37	3	SG70	192.00	46.80	117.00	
37	3	SG70	192.00	49.20	119.34	
37	3	SG70	192.00	56.40	120.51	
37	3	SG70	192.00	57.60	121.68	
37	3	SG70	192.00	60.00	120.51	
37	3	SG70	192.00	66.00	121.68	120.4
38	1	PCC	6.00	6.00	136.02	
38	2	CL5S	5.00	6.00	136.02	
38	2	CL5S	5.00	11.00	129.13	132.6
38	3	SG12	192.00	11.00	129.13	
38	3	SG12	192.00	17.00	109.24	
38	3	SG12	192.00	18.20	111.38	
38	3	SG12	192.00	23.00	114.80	
38	3	SG12	192.00	30.20	116.26	
38	3	SG12	192.00	32.60	111.18	
38	3	SG12	192.00	41.00	106.61	
38	3	SG12	192.00	49.40	109.24	
38	3	SG12	192.00	50.60	108.37	
38	3	SG12	192.00	53.00	106.61	
38	3	SG12	192.00	59.00	109.65	
38	3	SG12	192.00	62.60	107.43	
38	3	SG12	192.00	74.60	108.47	109.9
39	1	PCC	6.00	6.00	138.67	
39	2	CL5S	5.00	6.00	138.67	
39	2	CL5S	5.00	11.00	117.59	
39	3	SG12	192.00	11.00	117.59	
39	3	SG12	192.00	14.60	109.65	
39	3	SG12	192.00	17.00	109.65	
39	3	SG12	192.00	26.60	111.80	
39	3	SG12	192.00	27.80	112.84	
39	3	SG12	192.00	30.20		
39	3	SG12	192.00	32.60	116.48	
39	3	SG12	192.00	35.00	115.36	
39	3	SG12	192.00	36.20	110.29	
39	3	SG12	192.00	41.00	112.25	
39	3	SG12	192.00	48.20	111.80	
39	3	SG12	192.00	51.80	107.50	
39	3	SG12	192.00	56.60	110.73	
39	3	SG12	192.00	57.80	111.80	112.1
39	3	SG12	192.00	68.60	108.17	
39	3	SG12	192.00	69.80	102.82	
39	3	SG12	192.00	79.40	104.28	
39	3	SG12	192.00	80.60	108.58	110.7

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Dry density (lb/ft^3)	
					Sample	Layer avg
40	1	PCC	6.25	6.25	132.70	
40	2	CL5S	5.00	6.25	132.70	
40	2	CL5S	5.00	11.25	132.93	
40	3	SG12	192.00	11.25	132.93	
40	3	SG12	192.00	12.45	108.17	
40	3	SG12	192.00	14.85	111.31	
40	3	SG12	192.00	16.05	108.58	
40	3	SG12	192.00	23.25	112.81	
40	3	SG12	192.00	29.25	113.12	
40	3	SG12	192.00	30.45	111.38	
40	3	SG12	192.00	37.65	109.24	
40	3	SG12	192.00	38.85	109.24	
40	3	SG12	192.00	41.25	110.85	
40	3	SG12	192.00	47.25	116.48	
40	3	SG12	192.00	49.65	116.48	
40	3	SG12	192.00	53.25	107.50	
40	3	SG12	192.00	56.85	112.00	
40	3	SG12	192.00	58.05	112.00	
40	3	SG12	192.00	64.05	112.00	
40	3	SG12	192.00	66.45	104.81	
40	3	SG12	192.00	70.05	109.65	
40	3	SG12	192.00	71.25	110.88	
40	3	SG12	192.00	88.05	107.50	
40	3	SG12	192.00	91.65	112.00	110.8

APPENDIX B: MN/ROAD SOIL MOISTURE CONTENT DATA FROM CONSTRUCTION RECORDS

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight)	
					Sample	Layer avg
1	1	AC	5.75	5.75		
1	2	CL4S	33.00	5.75	8.70	
1	2	CL4S	33.00	11.75	7.20	
1	2	CL4S	33.00	16.75	9.90	
1	2	CL4S	33.00	22.75	8.90	
1	2	CL4S	33.00	26.75	7.70	
1	2	CL4S	33.00	28.75	9.40	
1	2	CL4S	33.00	32.75	7.60	
1	2	CL4S	33.00	34.75	8.60	8.5
1	2	CL4S	33.00	38.75		
1	3	SG12	192.00	38.75	14.81	
1	3	SG12	192.00	49.55	17.20	
1	3	SG12	192.00	55.55	16.83	16.3
2	1	AC	5.75	5.75		
2	2	CL6S	4.00	5.75	5.03	
2	2	CL6S	4.00	8.75	7.00	6.0
2	2	CL6S	4.00	9.75	9.30	
2	3	CL4S	28.00	9.75	9.30	
2	3	CL4S	28.00	15.75	9.10	
2	3	CL4S	28.00	21.75	7.60	
2	3	CL4S	28.00	27.75	9.20	8.9
2	3	CL4S	28.00	37.75	14.51	
2	3	CL4S	28.00	44.95	13.88	
2	3	CL4S	28.00	59.35	16.12	
2	4	SG12	192.00	37.75	14.51	
2	4	SG12	192.00	44.95	13.88	
2	4	SG12	192.00	59.35	16.12	14.8
3	1	AC	5.75	5.75		
3	2	CL5S	4.00	5.75	6.48	6.5
3	2	CL5S	4.00	9.75	6.48	
3	3	CL3S	33.00	9.75	6.48	
3	3	CL3S	33.00	14.75	7.04	
3	3	CL3S	33.00	20.75	7.84	
3	3	CL3S	33.00	26.75	7.84	
3	3	CL3S	33.00	34.75	7.68	7.2
3	3	CL3S	33.00	47.55	15.40	
3	4	SG12	192.00	47.55	15.40	15.4
4	2	SG12	192.00	41.15	16.29	
4	2	SG12	192.00	45.95	16.65	
4	2	SG12	192.00	53.15	15.33	16.6

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight)	
					Sample	Layer avg
5	1	PCC	7.50	7.50		
5	2	CL4S	3.00	7.50	8.04	8.0
5	3	CL3S	27.00	13.50	7.60	
5	3	CL3S	27.00	16.50	6.32	
5	3	CL3S	27.00	22.50	8.00	
5	3	CL3S	27.00	28.50	7.04	7.2
5	3	CL3S	27.00	39.90	17.01	
5	3	CL3S	27.00	43.50	15.96	
5	3	CL3S	27.00	44.70	15.96	
5	3	CL3S	27.00	45.90	13.59	
5	4	SG12	192.00	39.90	17.01	
5	4	SG12	192.00	43.50	15.96	
5	4	SG12	192.00	44.70	15.96	
5	4	SG12	192.00	45.90	13.59	15.6
6	1	PCC	7.50	7.50	8.90	
6	2	CL4S	5.00	7.50	8.90	8.9
6	3	SG12	192.00	17.30	13.53	
6	3	SG12	192.00	18.50	15.39	
6	3	SG12	192.00	19.70	15.85	
6	3	SG12	192.00	23.30	17.98	
6	3	SG12	192.00	37.70	15.96	
6	3	SG12	192.00	46.10	15.48	
6	3	SG12	192.00	47.30	14.54	
6	3	SG12	192.00	58.10	14.36	15.4
7	1	PCC	7.50	7.50		
7	2	PASB	4.00	7.50	7.80	7.8
7	4	SG12	192.00	18.10	14.80	
7	4	SG12	192.00	21.70	17.44	
7	4	SG12	192.00	22.90	14.60	
7	4	SG12	192.00	25.30	15.33	
7	4	SG12	192.00	26.50	13.59	
7	4	SG12	192.00	32.50	15.64	
7	4	SG12	192.00	40.90	15.17	
7	4	SG12	192.00	45.70	15.96	
7	4	SG12	192.00	62.50	14.69	
7	4	SG12	192.00	69.70	17.56	15.5
8	1	PCC	7.50	7.50		
8	2	PASB	4.00	7.50	8.40	
8	3	CL4S	3.00	16.90		
8	4	SG12	192.00	16.90	17.74	
8	4	SG12	192.00	18.10	13.58	
8	4	SG12	192.00	20.50	13.88	
8	4	SG12	192.00	22.90	15.84	
8	4	SG12	192.00	33.70	15.96	
8	4	SG12	192.00	40.90	15.48	
8	4	SG12	192.00	45.70	15.17	
8	4	SG12	192.00	48.10	12.64	
8	4	SG12	192.00	55.30	13.88	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
8	4	SG12	192.00	62.50	13.43	
8	4	SG12	192.00	69.70	15.93	14.9
9	1	PCC	7.50	7.50		
9	2	PASB	4.00	7.50	8.30	8.3
9	4	SG12	192.00	18.10	14.81	
9	4	SG12	192.00	39.70	15.48	
9	4	SG12	192.00	43.30	12.46	
9	4	SG12	192.00	45.70	14.70	
9	4	SG12	192.00	48.10	16.38	
9	4	SG12	192.00	49.30	16.91	
9	4	SG12	192.00	50.50	17.38	
9	4	SG12	192.00	55.30	13.17	15.2
10	1	PCC	9.50	9.50		
10	2	PASB	4.00	9.50	8.00	8.0
10	4	SG12	192.00	24.90	14.06	
10	4	SG12	192.00	28.50	14.69	
10	4	SG12	192.00	33.30	15.96	
10	4	SG12	192.00	35.70	15.48	
10	4	SG12	192.00	44.10	15.20	
10	4	SG12	192.00	50.10	11.52	
10	4	SG12	192.00	57.30	12.69	14.2
10	4	SG12	192.00	59.70	20.83	20.8
11	1	PCC	9.50	9.50		
11	2	CL5S	5.00	9.50	8.10	8.1
11	3	SG12	192.00	21.70	13.94	
11	3	SG12	192.00	28.90	15.64	
11	3	SG12	192.00	32.50	14.69	
11	3	SG12	192.00	38.50	14.54	
11	3	SG12	192.00	43.30	16.12	
11	3	SG12	192.00	48.10	13.53	
11	3	SG12	192.00	51.70	17.01	
11	3	SG12	192.00	54.10	11.36	
11	3	SG12	192.00	56.50	12.02	14.3
12	1	PCC	9.50	9.50		
12	2	CL5S	5.00	9.50	6.72	6.7
12	3	SG12	192.00	20.50	14.38	
12	3	SG12	192.00	21.70	13.62	
12	3	SG12	192.00	26.50	14.54	
12	3	SG12	192.00	32.50	15.96	
12	3	SG12	192.00	33.70	15.96	
12	3	SG12	192.00	43.30	16.83	
12	3	SG12	192.00	46.90	13.36	
12	3	SG12	192.00	48.10	11.86	14.6
13	1	PCC	9.50	0.00	7.80	
13	1	PCC	9.50	9.50		
13	2	CL5S	5.00	9.50	6.16	6.2

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight)	
					Sample	Layer avg
13	3	SG12	192.00	22.90	12.59	
13	3	SG12	192.00	24.00	13.26	
13	3	SG12	192.00	30.10	15.20	
13	3	SG12	192.00	32.50	16.65	
13	3	SG12	192.00	42.10	18.46	
13	3	SG12	192.00	43.30	16.47	
13	3	SG12	192.00	49.30	10.74	
13	3	SG12	192.00	56.50	18.69	15.3
14	1	AC	10.75	0.00	7.45	
14	1	AC	10.75	2.40	12.51	
14	1	AC	10.75	4.80	14.87	
14	1	AC	10.75	7.20	16.77	
14	1	AC	10.75	9.60	14.26	
14	1	AC	10.75	10.75		
14	2	SG12	192.00	10.75	12.96	
14	2	SG12	192.00	10.80	17.03	
14	2	SG12	192.00	12.00	11.60	
14	2	SG12	192.00	13.20	15.27	
14	2	SG12	192.00	15.60	13.43	
14	2	SG12	192.00	19.20	15.12	
14	2	SG12	192.00	20.35	14.07	
14	2	SG12	192.00	20.40	14.84	
14	2	SG12	192.00	22.80	15.36	
14	2	SG12	192.00	24.00	13.86	
14	2	SG12	192.00	25.15	14.36	
14	2	SG12	192.00	27.60	13.86	
14	2	SG12	192.00	31.20	13.75	14.3
14	2	SG12	192.00	33.55	17.56	
14	2	SG12	192.00	36.00	17.70	
14	2	SG12	192.00	37.20	16.77	
14	2	SG12	192.00	38.40	17.80	
14	2	SG12	192.00	39.55	14.22	
14	2	SG12	192.00	41.95	18.10	
14	2	SG12	192.00	42.00	16.54	
14	2	SG12	192.00	45.60	17.10	
14	2	SG12	192.00	49.15	15.05	
14	2	SG12	192.00	49.20	18.45	
14	2	SG12	192.00	50.40	12.74	
14	2	SG12	192.00	52.80	18.72	
14	2	SG12	192.00	56.35	18.06	
14	2	SG12	192.00	60.00	13.65	
14	2	SG12	192.00	63.60	18.94	
14	2	SG12	192.00	66.00	16.56	
14	2	SG12	192.00	102.00	14.43	16.5
15	1	AC	10.75	0.00	6.20	
15	1	AC	10.75	3.60	17.51	
15	1	AC	10.75	4.80	16.38	
15	1	AC	10.75	6.00	11.89	
15	1	AC	10.75	8.40	16.64	?
15	2	SG12	192.00	10.80	17.41	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
15	2	SG12	192.00	16.80	16.56	
15	2	SG12	192.00	17.95	12.62	
15	2	SG12	192.00	19.20	17.65	
15	2	SG12	192.00	20.40	15.48	
15	2	SG12	192.00	21.55	14.20	
15	2	SG12	192.00	21.60	20.40	
15	2	SG12	192.00	24.00	16.19	
15	2	SG12	192.00	25.20	13.53	
15	2	SG12	192.00	28.75	15.58	
15	2	SG12	192.00	28.80	16.20	
15	2	SG12	192.00	29.95	15.64	16.0
15	2	SG12	192.00	33.60	16.82	
15	2	SG12	192.00	36.00	15.80	
15	2	SG12	192.00	38.40	16.58	
15	2	SG12	192.00	39.55	14.85	
15	2	SG12	192.00	40.75	16.65	
15	2	SG12	192.00	40.80	15.84	
15	2	SG12	192.00	42.00	14.43	
15	2	SG12	192.00	46.80	17.46	
15	2	SG12	192.00	47.95	18.52	
15	2	SG12	192.00	48.00	18.05	
15	2	SG12	192.00	49.20	17.53	
15	2	SG12	192.00	54.00	17.86	
15	2	SG12	192.00	56.35	16.53	
15	2	SG12	192.00	56.40	13.28	
15	2	SG12	192.00	60.00	21.39	
15	2	SG12	192.00	69.60	16.28	
15	2	SG12	192.00	80.40	19.75	16.9
16	1	AC	7.75	7.75	7.84	
16	2	CL3S	28.00	7.75	7.84	
16	2	CL3S	28.00	11.75	7.84	
16	2	CL3S	28.00	17.75	7.52	
16	2	CL3S	28.00	23.75	7.20	
16	2	CL3S	28.00	29.75	7.52	7.6
16	3	SG12	192.00	39.35	11.85	
16	3	SG12	192.00	44.15	19.50	
16	3	SG12	192.00	51.35	16.49	
16	3	SG12	192.00	52.55	19.11	
16	3	SG12	192.00	54.95	16.64	
16	3	SG12	192.00	57.35	15.62	
16	3	SG12	192.00	90.95	14.87	16.3
17	1	AC	7.75	7.75	7.92	
17	2	CL3S	28.00	7.75	7.92	
17	2	CL3S	28.00	11.75	7.40	
17	2	CL3S	28.00	17.75	8.00	
17	2	CL3S	28.00	23.75	6.32	
17	2	CL3S	28.00	29.75	7.52	7.4
17	3	SG12	192.00	40.55	17.64	
17	3	SG12	192.00	47.75	20.09	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
17	3	SG12	192.00	48.00	19.47	
17	3	SG12	192.00	51.35	17.14	
17	3	SG12	192.00	52.55	16.99	
17	3	SG12	192.00	53.75	21.00	
17	3	SG12	192.00	58.55	17.14	
17	3	SG12	192.00	59.75	18.23	18.5
17	3	SG12	192.00	75.35	13.81	
17	3	SG12	192.00	119.75	14.24	14.0
18	1	AC	7.75	7.75	6.92	
18	2	CL6S	12.00	7.75	6.92	
18	2	CL6S	12.00	9.75	7.12	
18	2	CL6S	12.00	13.75	6.41	6.8
18	3	CL3S	9.00	29.95	13.43	
18	4	SG12	192.00	29.95	13.43	
18	4	SG12	192.00	38.35	15.17	
18	4	SG12	192.00	44.35	13.81	
18	4	SG12	192.00	47.95	16.65	
18	4	SG12	192.00	53.95	18.23	
18	4	SG12	192.00	58.75	13.59	
18	4	SG12	192.00	62.35	17.32	
18	4	SG12	192.00	64.75	17.88	
18	4	SG12	192.00	92.35	11.86	15.3
19	1	AC	7.75	7.75	8.08	
19	2	CL3S	28.00	7.75	8.08	
19	2	CL3S	28.00	11.75	7.04	
19	2	CL3S	28.00	17.75	8.00	
19	2	CL3S	28.00	23.75	7.44	
19	2	CL3S	28.00	29.75	6.40	7.4
19	3	SG12	192.00	41.75	16.56	
19	3	SG12	192.00	48.95	16.70	
19	3	SG12	192.00	53.75	17.03	
19	3	SG12	192.00	58.55	13.27	
19	3	SG12	192.00	66.95	16.53	
19	3	SG12	192.00	78.95	13.90	
19	3	SG12	192.00	96.95	17.52	
19	3	SG12	192.00	100.55	14.38	
19	3	SG12	192.00	118.55	12.97	
19	3	SG12	192.00	123.35	17.64	
19	3	SG12	192.00	142.55	12.97	
19	3	SG12	192.00	150.95	13.10	
19	3	SG12	192.00	155.75	17.20	15.4
20	1	AC	7.75	7.75	7.16	
20	2	CL3S	28.00	7.75	7.16	
20	2	CL3S	28.00	14.75	7.04	
20	2	CL3S	28.00	20.75	8.00	
20	2	CL3S	28.00	23.75	7.28	
20	2	CL3S	28.00	29.75	6.40	7.2
20	2	CL3S	28.00	35.75	15.96	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
20	3	SG12	192.00	35.75	15.96	
20	3	SG12	192.00	47.75	13.53	
20	3	SG12	192.00	57.35	17.58	
20	3	SG12	192.00	63.35	16.74	
20	3	SG12	192.00	65.75	18.88	
20	3	SG12	192.00	77.75	14.06	
20	3	SG12	192.00	82.55	16.12	
20	3	SG12	192.00	99.35	17.70	16.3
20	3	SG12	192.00	101.75	9.28	
20	3	SG12	192.00	106.55	13.63	
20	3	SG12	192.00	111.35	6.78	
20	3	SG12	192.00	112.55	9.04	
20	3	SG12	192.00	114.95	13.90	
20	3	SG12	192.00	119.75	14.38	
20	3	SG12	192.00	123.35	10.35	
20	3	SG12	192.00	124.55	14.16	
20	3	SG12	192.00	129.35	7.38	
20	3	SG12	192.00	134.15	10.95	
20	3	SG12	192.00	148.55	11.19	
20	3	SG12	192.00	150.95	10.95	
20	3	SG12	192.00	159.35	11.04	11.0
21	2	CL5S	23.00	11.75	6.24	
21	2	CL5S	23.00	12.75	6.40	
21	2	CL5S	23.00	18.75	5.99	
21	2	CL5S	23.00	24.75	7.25	6.5
21	2	CL5S	23.00	30.75	15.33	
21	3	SG12	192.00	30.75	15.33	
21	3	SG12	192.00	39.15	14.36	
21	3	SG12	192.00	46.35	16.38	
21	3	SG12	192.00	47.55	16.83	
21	3	SG12	192.00	54.75	15.62	
21	3	SG12	192.00	55.95	12.09	
21	3	SG12	192.00	57.15	14.22	
21	3	SG12	192.00	71.55	19.89	15.6
22	1	AC	7.75	7.75	6.80	
22	2	CL6S	18.00	7.75	6.80	
22	2	CL6S	18.00	13.75	5.71	
22	2	CL6S	18.00	19.75	5.24	5.9
22	3	SG12	192.00	30.55	19.86	
22	3	SG12	192.00	32.95	13.59	
22	3	SG12	192.00	37.75	14.84	
22	3	SG12	192.00	43.75	15.48	
22	3	SG12	192.00	45.60	12.32	
22	3	SG12	192.00	47.35	16.49	
22	3	SG12	192.00	56.95	15.96	
22	3	SG12	192.00	59.35	16.20	
22	3	SG12	192.00	71.35	17.42	
22	3	SG12	192.00	80.95	6.62	14.9

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight)	
					Sample	Layer avg
22	3	SG12	192.00	95.35	12.57	
22	3	SG12	192.00	133.75	5.95	9.3
23	1	AC	8.75	8.75	8.20	
23	2	PASB	4.00	8.75	8.20	8.2
23	3	CL4S	3.00	15.75	16.03	
23	4	SG12	192.00	15.75	16.03	
23	4	SG12	192.00	27.75	20.27	
23	4	SG12	192.00	32.55	14.69	
23	4	SG12	192.00	39.75	16.65	
23	4	SG12	192.00	46.95	14.85	
23	4	SG12	192.00	51.75	14.76	
23	4	SG12	192.00	61.35	11.53	
23	4	SG12	192.00	66.15	17.54	
23	4	SG12	192.00	76.95	11.53	15.3
24	1	AC	3.00	3.00	4.62	
24	2	CL6S	4.00	3.00	4.62	
24	2	CL6S	4.00	7.00	11.93	
24	3	SG70	192.00	7.00	11.93	
24	3	SG70	192.00	16.60	4.19	
24	3	SG70	192.00	20.20	4.93	
24	3	SG70	192.00	22.60	13.11	
24	3	SG70	192.00	25.00	8.75	
24	3	SG70	192.00	27.40	2.97	7.6
25	1	AC	5.00	5.00	12.13	
25	2	SG70	192.00	5.00	12.13	
25	2	SG70	192.00	17.00	8.70	
25	2	SG70	192.00	18.20	4.59	
25	2	SG70	192.00	19.40	8.49	
25	2	SG70	192.00	20.60	8.80	
25	2	SG70	192.00	24.20	4.19	7.8
26	1	AC	6.00	6.00	15.49	
26	2	SG12	192.00	6.00	15.49	
26	2	SG12	192.00	16.80	15.67	
26	2	SG12	192.00	19.20	16.73	
26	2	SG12	192.00	43.20	15.17	
26	2	SG12	192.00	45.60	15.93	
26	2	SG12	192.00	46.80	17.56	
26	2	SG12	192.00	49.20	15.96	
26	2	SG12	192.00	55.20	14.69	
26	2	SG12	192.00	93.60	17.92	16.1
27	2	CL6S	11.00	9.00	6.39	
27	2	CL6S	11.00	14.00	15.13	
27	3	SG12	192.00	14.00	15.13	
27	3	SG12	192.00	29.60	16.24	
27	3	SG12	192.00	48.80	14.85	
27	3	SG12	192.00	56.00	16.12	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
27	3	SG12	192.00	64.40	15.20	
27	3	SG12	192.00	65.60	17.06	15.8
28	1	AC	3.00	3.00	6.89	
28	2	CL5S	13.00	3.00	6.89	
28	2	CL5S	13.00	7.00	7.21	
28	2	CL5S	13.00	10.00	6.16	6.8
28	2	CL5S	13.00	16.00	14.58	
28	3	SG12	192.00	16.00	14.58	
28	3	SG12	192.00	28.00	16.60	
28	3	SG12	192.00	32.80	14.06	
28	3	SG12	192.00	40.00	15.09	
28	3	SG12	192.00	41.20	15.96	
28	3	SG12	192.00	42.40	15.41	
28	3	SG12	192.00	47.20	12.47	
28	3	SG12	192.00	54.40	13.53	
28	3	SG12	192.00	58.00	14.48	14.7
29	1	AC	5.00	5.00	8.30	
29	2	CL4S	10.00	5.00	8.30	
29	2	CL4S	10.00	11.00	7.50	7.9
29	2	CL4S	10.00	15.00	14.48	
29	3	SG12	192.00	15.00	14.48	
29	3	SG12	192.00	21.00	17.03	
29	3	SG12	192.00	30.60	15.64	
29	3	SG12	192.00	34.20	16.65	
29	3	SG12	192.00	35.40	14.69	
29	3	SG12	192.00	36.60	14.98	
29	3	SG12	192.00	42.60	16.12	
29	3	SG12	192.00	49.80	15.12	
29	3	SG12	192.00	58.20	14.22	15.4
30	1	AC	5.00	5.00	6.08	
30	2	CL3S	12.00	5.00	6.08	
30	2	CL3S	12.00	11.00	7.12	6.6
30	2	CL3S	12.00	17.00	13.90	
30	3	SG12	192.00	17.00	13.90	
30	3	SG12	192.00	24.20	15.57	
30	3	SG12	192.00	27.80	16.13	
30	3	SG12	192.00	33.80	15.17	
30	3	SG12	192.00	37.40	15.64	
30	3	SG12	192.00	43.40	15.02	
30	3	SG12	192.00	48.20	16.59	
30	3	SG12	192.00	51.80	12.64	
30	3	SG12	192.00	59.00	14.22	15.0
31	1	AC	3.00	3.00	7.21	
31	2	CL5S	4.00	3.00	7.21	
31	3	CL3S	12.00	9.00	7.28	
31	3	CL3S	12.00	27.40	15.75	

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
31	4	SG12	192.00	27.40	15.75	
31	4	SG12	192.00	33.40	14.22	
31	4	SG12	192.00	34.60	15.96	
31	4	SG12	192.00	41.80	15.93	
31	4	SG12	192.00	47.80	15.75	
31	4	SG12	192.00	53.80	16.03	
31	4	SG12	192.00	58.60	16.75	
31	4	SG12	192.00	63.40	16.64	15.9
32	1	CL1C	12.00	0.00	7.47	
32	1	CL1C	12.00	6.00	8.01	7.7
32	1	CL1C	12.00	12.00	14.06	
32	2	SG12	192.00	12.00	14.06	
32	2	SG12	192.00	18.00	15.39	
32	2	SG12	192.00	32.40	14.69	
32	2	SG12	192.00	40.80	16.12	
32	2	SG12	192.00	48.00	14.85	
32	2	SG12	192.00	50.40	15.17	
32	2	SG12	192.00	57.60	16.65	
32	2	SG12	192.00	70.80	15.93	
32	2	SG12	192.00	84.00	16.28	
32	2	SG12	192.00	88.80	11.38	
32	2	SG12	192.00	93.60	15.48	
32	2	SG12	192.00	100.80	13.27	
32	2	SG12	192.00	103.20	11.85	14.7
33	1	CL1C	12.00	0.00	7.74	
33	1	CL1C	12.00	6.00	8.19	8.0
33	1	CL1C	12.00	12.00	18.52	
33	2	SG12	192.00	12.00	18.52	
33	2	SG12	192.00	13.20	18.52	
33	2	SG12	192.00	22.80	17.03	
33	2	SG12	192.00	28.80	16.87	
33	2	SG12	192.00	32.40	14.03	
33	2	SG12	192.00	49.20	15.96	
33	2	SG12	192.00	52.80	15.94	
33	2	SG12	192.00	73.20	17.06	
33	2	SG12	192.00	84.00	19.86	16.9
34	1	CL1F	12.00	0.00	9.05	
34	1	CL1F	12.00	6.00	8.94	9.0
34	2	SG12	192.00	18.00	13.11	
34	2	SG12	192.00	19.20	17.20	
34	2	SG12	192.00	27.60	16.37	
34	2	SG12	192.00	28.80	16.70	
34	2	SG12	192.00	30.00	16.53	
34	2	SG12	192.00	46.80	15.33	
34	2	SG12	192.00	54.00	16.12	
34	2	SG12	192.00	55.20	15.75	
34	2	SG12	192.00	62.40	17.54	
34	2	SG12	192.00	64.80	12.69	15.7

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight)	
					Sample	Layer avg
35	1	CL1F	12.00	0.00	7.41	
35	1	CL1F	12.00	6.00	7.74	7.6
35	2	SG12	192.00	20.40	15.56	
35	2	SG12	192.00	22.80	13.59	
35	2	SG12	192.00	28.80	16.37	
35	2	SG12	192.00	30.00	16.37	
35	2	SG12	192.00	36.00	13.59	
35	2	SG12	192.00	45.60	17.27	
35	2	SG12	192.00	58.80	11.69	14.9
36	1	PCC	6.00	6.00	6.08	
36	2	CL5S	5.00	6.00	6.08	6.1
36	2	CL5S	5.00	11.00	13.43	
36	3	SG70	192.00	11.00	13.43	
36	3	SG70	192.00	12.20	9.05	
36	3	SG70	192.00	14.60	9.00	
36	3	SG70	192.00	15.80	9.18	
36	3	SG70	192.00	17.00	9.25	
36	3	SG70	192.00	19.40	7.63	
36	3	SG70	192.00	21.80	7.53	
36	3	SG70	192.00	23.00	7.00	
36	3	SG70	192.00	26.60	11.48	
36	3	SG70	192.00	27.80	11.61	9.5
37	1	PCC	6.00	6.00	6.72	
37	2	CL5S	12.00	6.00	6.72	
37	2	CL5S	12.00	12.00	8.10	7.4
37	3	SG70	192.00	20.40	8.91	
37	3	SG70	192.00	21.60	9.05	
37	3	SG70	192.00	25.20	8.16	
37	3	SG70	192.00	26.40	8.48	
37	3	SG70	192.00	27.60	8.06	
37	3	SG70	192.00	31.20	8.06	
37	3	SG70	192.00	33.60	11.07	
37	3	SG70	192.00	37.20	11.34	9.1
38	1	PCC	6.00	6.00	6.32	
38	2	CL5S	5.00	6.00	6.32	6.3
38	2	CL5S	5.00	11.00	15.57	
38	3	SG12	192.00	11.00	15.57	
38	3	SG12	192.00	14.60	17.38	
38	3	SG12	192.00	17.00	15.33	
38	3	SG12	192.00	27.80	16.53	
38	3	SG12	192.00	33.80	16.65	
38	3	SG12	192.00	36.20	16.24	
38	3	SG12	192.00	48.20	15.17	
38	3	SG12	192.00	56.60	16.75	
38	3	SG12	192.00	61.40	15.58	
38	3	SG12	192.00	62.60	14.16	
38	3	SG12	192.00	74.60	13.26	15.7

Cell	Layer	Material type	Layer thickness (in.)	Sample depth (top) (in.)	Moisture content (% dry weight) Sample	Layer avg
39	1	PCC	6.00	6.00	6.72	
39	2	CL5S	5.00	6.00	6.72	6.7
39	2	CL5S	5.00	11.00	14.61	
39	3	SG12	192.00	11.00	14.61	
39	3	SG12	192.00	12.20	17.07	
39	3	SG12	192.00	30.20	16.56	
39	3	SG12	192.00	32.60	17.74	
39	3	SG12	192.00	42.20	13.86	
39	3	SG12	192.00	50.60	15.03	
39	3	SG12	192.00	57.80	15.64	
39	3	SG12	192.00	84.20	24.36	
39	3	SG12	192.00	85.40	15.17	16.7
40	1	PCC	6.25	6.25	6.89	
40	2	CL5S	5.00	6.25	6.89	
40	2	CL5S	5.00	11.25	17.77	
40	3	SG12	192.00	11.25	17.77	
40	3	SG12	192.00	13.65	17.09	
40	3	SG12	192.00	26.85	16.73	
40	3	SG12	192.00	32.85	15.57	
40	3	SG12	192.00	35.25	14.84	
40	3	SG12	192.00	41.25	12.32	
40	3	SG12	192.00	49.65	15.64	
40	3	SG12	192.00	56.85	14.85	
40	3	SG12	192.00	70.05	16.28	
40	3	SG12	192.00	71.25	17.06	
40	3	SG12	192.00	77.25	15.64	
40	3	SG12	192.00	89.25	16.64	
40	3	SG12	192.00	96.45	10.90	15.5

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